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MATHEMATICAL SIMULATION OF AMMONIA STRIPPING TOWERS FOR WASTEWATER TREATMENT

Joseph F. Roesler, et al

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By

Joseph F. Roesler

Robert Smith

Richard G. Eilers

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16. Abstracts

This computer program (FORTRAN, IBM 1130) can be used for preliminary design and cost estimation of ammonia stripping towers and cooling towers used in the treatment of wastewater. Crosscurrent and countercurrent tower configurations are included in the program. This mathematical model considers the effect of temperature drop throughout the stripping tower. Capital and operation and maintenance costs are also calculated.

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This report describes a digital computer program for design of ammonia stripping and cooling towers. The ammonia stripping portion of the program is embedded in the cooling tower calculation in order that the variation of Henry's Law constant with water temperature can be taken into account. The logic of the program is arranged for (1) design of cooling towers and (2) for design of ammonia stripping towers with temperature correction. Two tower configurations are included in the program (1) countercurrent in which the liquid flows down and the air moves upward and (2) crosscurrent in which the liquid flows down and the air moves horizontally at right angles to the flow of the liquid.

Design calculations are based on a numerical integration scheme similar to that described by Thibodeaux[1]. The numerical integration method used is the trapezoidal or "Modified Euler" method described by Milne[2]. This method computes the incremental change in the dependent variable as an average derivative multiplied by the incremental change in the independent variable. The average derivative is taken as the sum of the derivatives at the extremes of the increment divided by two.

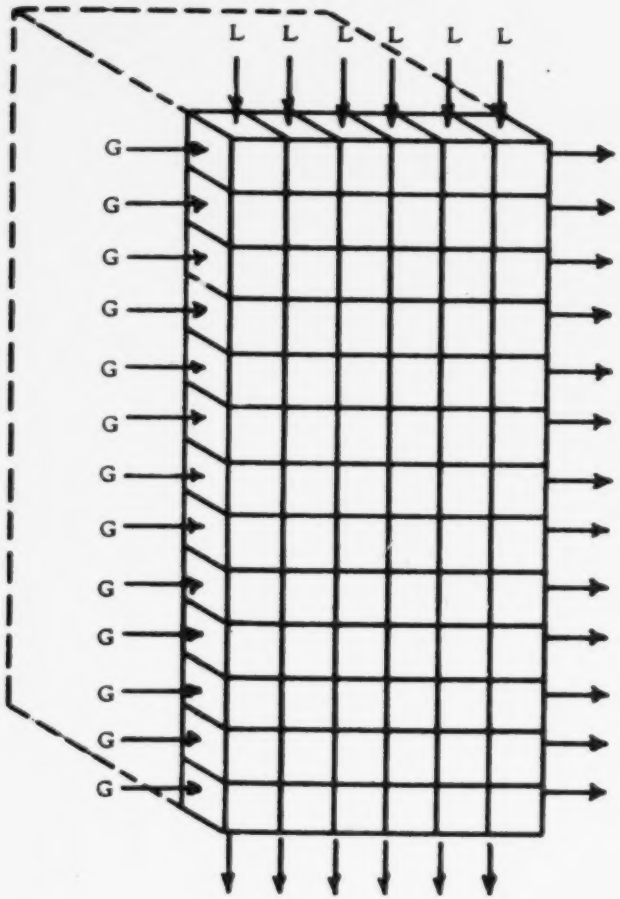
The cooling tower relationships were taken from McAdams[3] and the ammonia stripping relations were taken from Treybal[4].

CROSSCURRENT TOWERS

Consider first the crosscurrent tower shown diagramatically in Figure 1. A section of the tower one foot deep is considered. The liquid loading rate (L'), temperature, and ammonia concentration of the liquid stream entering the tower from the top are known and are

SCHEMATIC DIAGRAM FOR AMMONIA STRIPPING TOWERS

CROSSCURRENT TOWER



COUNTERCURRENT TOWER

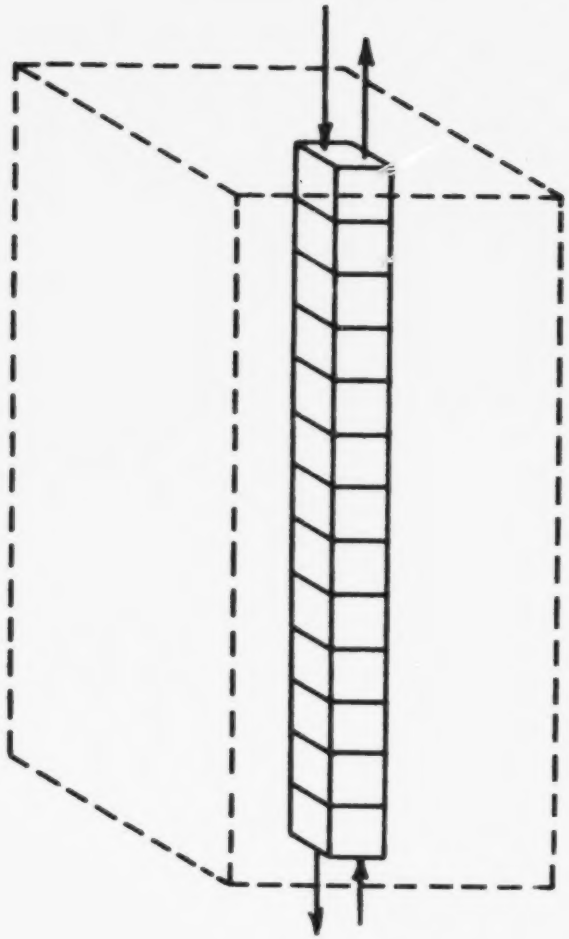
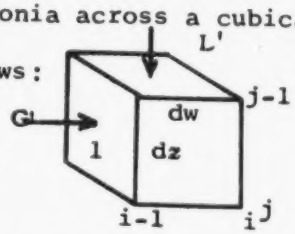


Figure 1

supplied as input to the program. The air mass flow rate (G'), the wet bulb temperature, and the ammonia concentration (zero) of the air entering from the left are known and supplied as input. The conservation of mass relationship for ammonia across a cubical element of the tower can then be written as follows:



$$G'(y_i - y_{i-1})dz = L'(x_{j-1} - x_j)dw \qquad (1)$$

where G' = air rate, lb moles/hr/sq ft

y = concentration of ammonia gas in air, mole fraction

dz = increment of tower height, ft

L' = liquid rate, lb moles/hr/sq ft

x = concentration of ammonia in water, mole fraction

dw = increment of tower width, ft

i = increment subscript increasing to the right

j = increment subscript increasing down the tower

Equation (1) can be summarized in incremental form as follows:

$$\Delta y = (\Delta w/\Delta z)(L'/G')\Delta x \qquad (2)$$

The rate at which ammonia is transferred from the liquid to the gas can be expressed as follows:

$$y_i - y_{i-1} = (1/H_a)(y^* - y)dw \qquad (3)$$

where H_a = overall height of a transfer unit for ammonia, ft

y* = concentration of ammonia in gas in equilibrium with the liquid at the midpoint of the incremental volume according to Henry's law, mole fraction

y = concentration of ammonia in the gas at the midpoint of the incremental volume, mole fraction

Henry's Law is given by the following equation:

$$y^* = mx \qquad (4)$$

m = Henry's Law constant, dimensionless

Concentration of dissolved ammonia expressed by (x) in the above equation refers to ammonia in the NH_3 form.

Ionic equilibrium theory, Butler[5], can be used to calculate, approximately, the fraction of the dissolved ammonia which exists in the NH_3 form. Factors such as ionic strength, water temperature, and the presence of organics must be taken into account if ionic equilibrium theory is used. In this program the pH of the water is assumed to be above 10.5 which is equivalent to assuming that all of the dissolved ammonia exists in the NH_3 form.

The relationship between water temperature and Henry's Law constant was derived from References 6 and 7. These data are shown plotted in Figures 2 and 3. The empirical relationship shown in Figures 2 and 3 and Figure 4 of Reference 8 is given by the following equation:

$$m = 0.1117\ e^{0.02612T} \qquad (5)$$

where T = water temperature, ^oF

It should be noted here that no direct measurements of height of a transfer unit for crosscurrent towers appears to be available in the literature. Reported measurements for countercurrent towers have been used in this report and this is discussed fully in the section of this report entitled EMPIRICAL MASS AND ENTHALPY TRANSFER RELATIONSHIPS.

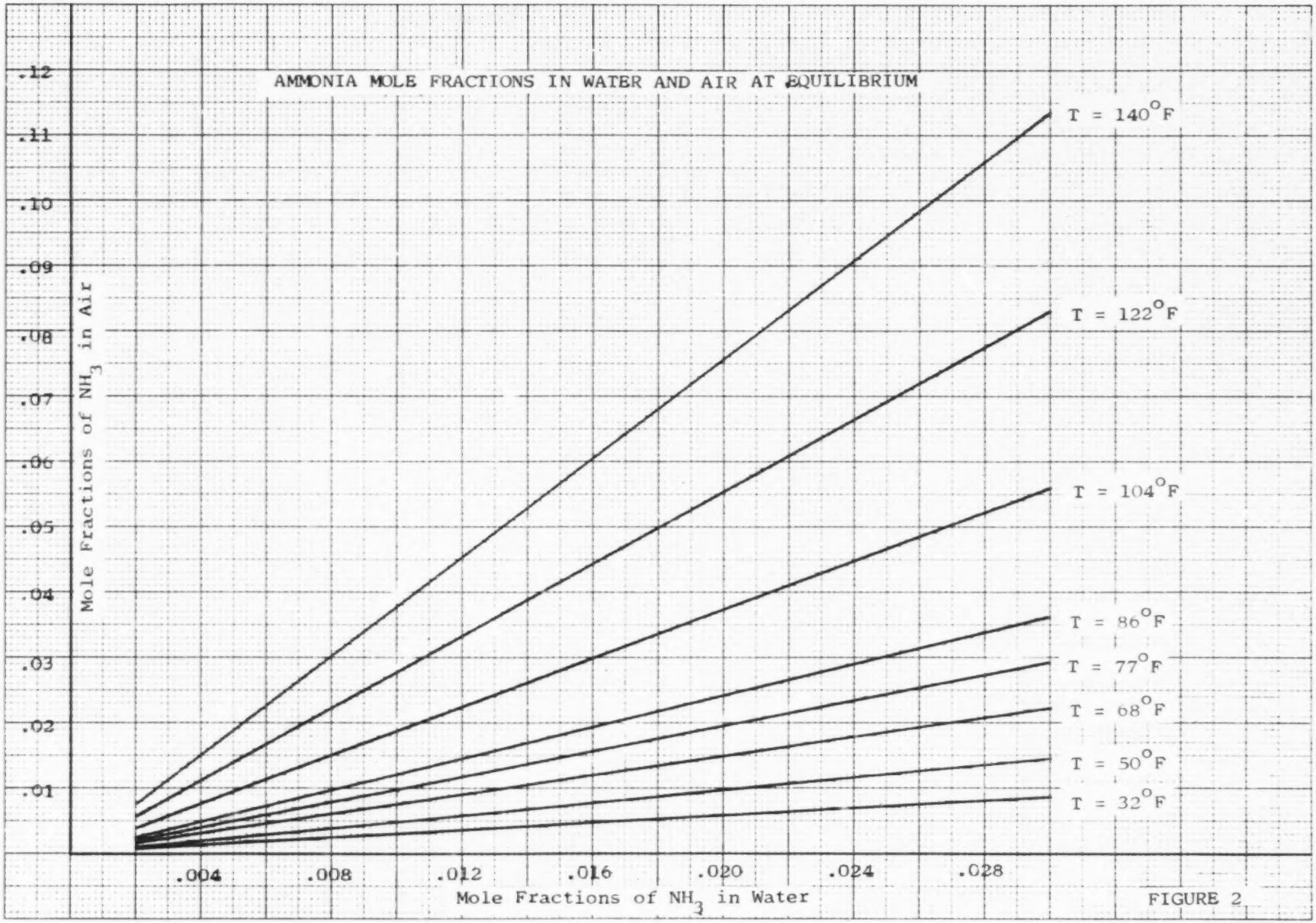

AMMONIA MOLE FRACTIONS IN WATER AND AIR AT EQUILIBRIUM
Mole Fractions of NH_3 in Air
.12
.11
.10
.09
.08
.07
.06
.05
.04
.03
.02
.01
T = 140°F
T = 122°F
T = 104°F
T = 86°F
T = 77°F
T = 68°F
T = 50°F
T = 32°F
.004
.008
.012
.016
.020
.024
.028
Mole Fractions of NH_3 in Water

FIGURE 2

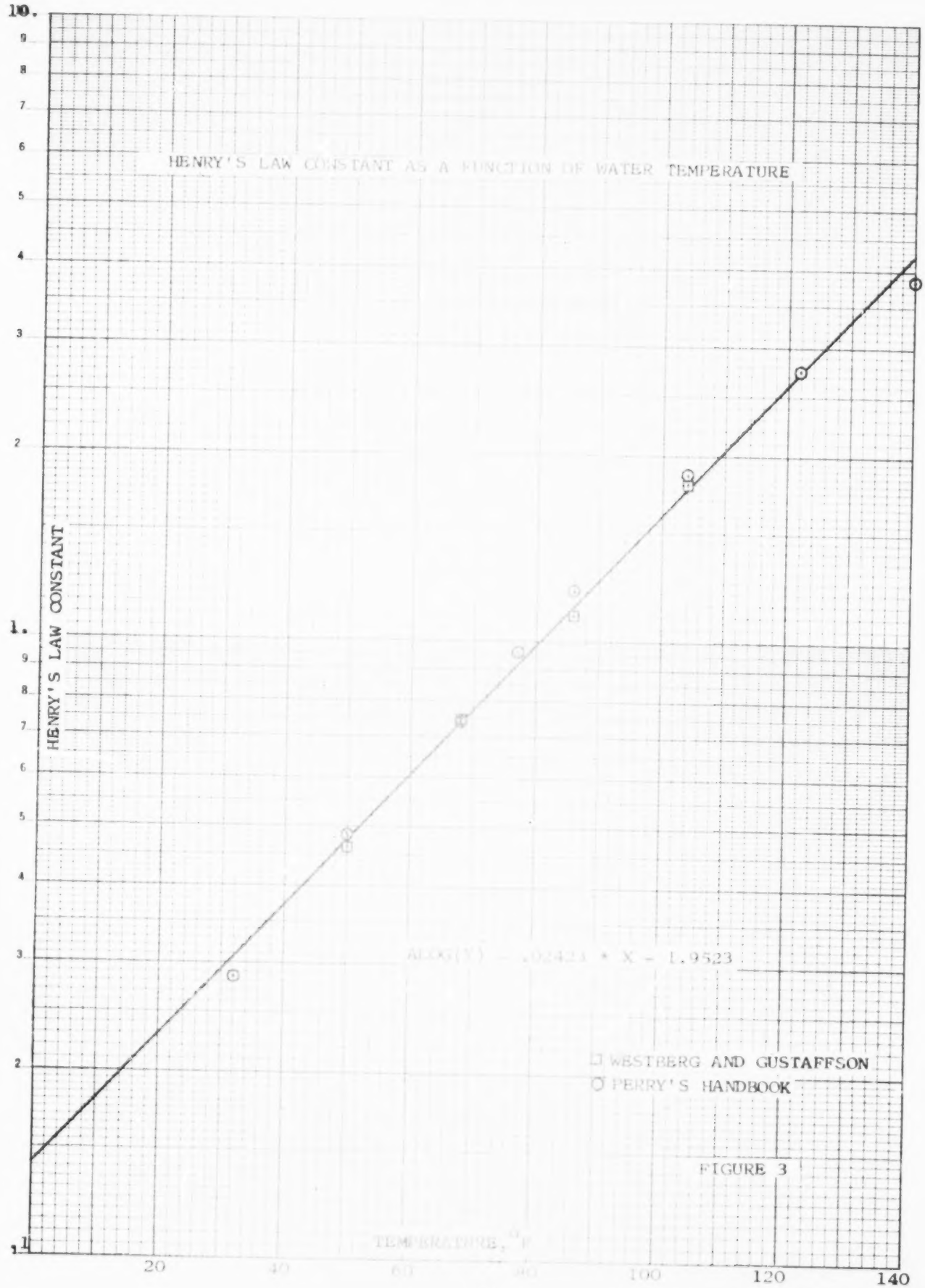

HENRY'S LAW CONSTANT AS A FUNCTION OF WATER TEMPERATURE
HENRY'S LAW CONSTANT
10.
9
8
7
6
5
4
3
2
1.
9
8
7
6
5
4
3
2
1
20
40
60
80
100
120
140
ALOG(Y) = .02423 * X - 1.9523
WESTBERG AND GUSTAFFSON
PERRY'S HANDBOOK

FIGURE 3

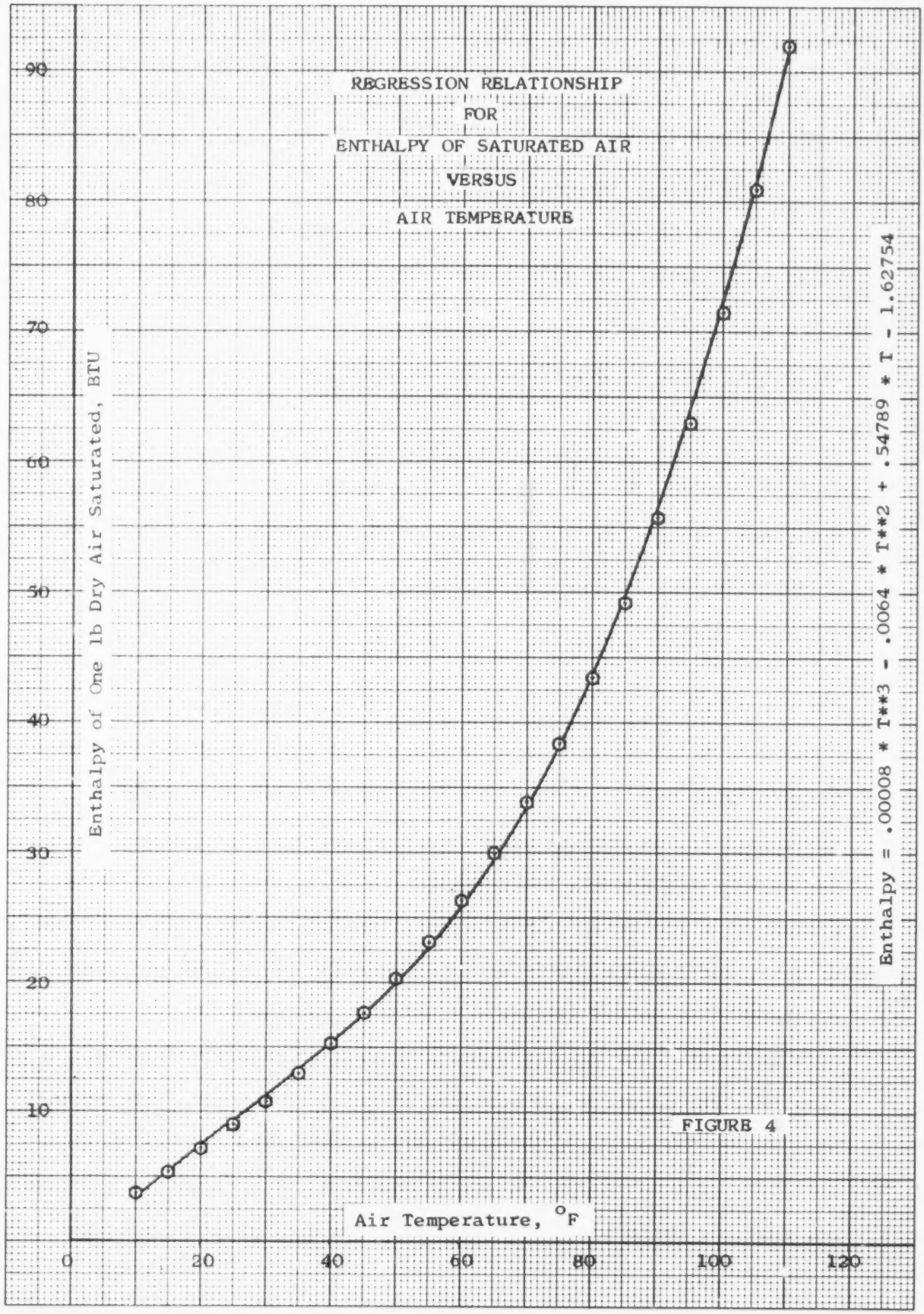

REGRESSION RELATIONSHIP
FOR
ENTHALPY OF SATURATED AIR
VERSUS
AIR TEMPERATURE
Enthalpy of One lb Dry Air Saturated, BTU
Air Temperature, °F
Enthalpy = .00008 * T**3 - .0064 * T**2 + .54789 * T - 1.62754
0
20
40
60
80
100
120
10
20
30
40
50
60
70
80
90

FIGURE 4

The numerical integration technique used for the crosscurrent case will now be described. Begin by agreeing to make dw equal to dz in every case. The mass balance relationship then becomes:

$$y_i - y_{i-1} = (L/G)(x_{j-1} - x_j) \qquad (6)$$

Using the "Modified Euler" Method the rate equation can be written as follows:

$$y_i - y_{i-1} = \frac{dw}{H_a}\left[\frac{m(x_j + x_{j-1})}{2} - \frac{y_i + y_{i-1}}{2}\right] \qquad (7)$$

Equations (6) and (7) can be solved simultaneously to give the following linear equation for x_j in terms of x_{j-1} and y_{i-1}:

$$x_j = \left[\frac{2(A/B) + A - m}{2(A/B) + A + m}\right] x_{j-1} + \left[\frac{2}{2(A/B) + A + m}\right] y_{i-1} \qquad (8)$$

where $A = L/G$

$B = dw/H_a$

Since we know the concentration of ammonia in the water entering a horizontal row of cubical elements from input or the previous calculation and we know the ammonia concentration in the air entering the cubical element from the left, each horizontal row of elements can be solved directly for ammonia stripping using equation (8). Each horizontal row of elements is solved in turn moving down the tower. The computation is terminated when the <u>average</u> ammonia concentration out of the last row is less than the target value supplied as input to the program. It has been found that good precision is obtained with the program when the increment of tower height is set at one foot. The computing time using one foot for dw is less than one minute for a tower 14 ft wide and 20-30 ft high.

Consider the crosscurrent tower used for cooling. Using the equations from McAdams[3] we can write the conservation of energy relationship as follows:

$$G\,(h_i - h_{i-1})dz = L\,(T_{j-1} - T_j)C_p\,dw \qquad (9)$$

C_p = specific heat of water, BTU/lb/^oF = 1.0

G = gas flow rate, lb/hr/sq ft

h = enthalpy of gas, BTU/lb

dz = height increment, ft

L = liquid flow rate, lb/hr/sq ft

T = water temperature, ^oF

dw = width increment, ft

Since it was agreed to set dw = dz, this equation can be simplified as follows:

$$h_i - h_{i-1} = (L/G)(T_{j-1} - T_j) \qquad (10)$$

The rate of enthalpy transfer between air and water can be expressed by the following equation:

$$h_i - h_{i-1} = (1/H_t)(h^* - h)dw \qquad (11)$$

where H_t = height of a transfer unit for cooling, ft

h* = enthalpy of air saturated with water vapor at the temperature of the water at the center of the element, BTU/lb of dry air

h = enthalpy of the air at the center of the element, BTU/lb of dry air

dw = width increment, ft

The empirical regression relationships between wet bulb temperature of the air and enthalpy of one pound of air saturated with water vapor is shown in Figures 4 and 5. This data was also taken from Perry's Handbook[6]. Notice that the dry bulb temperature of the air is never used in the cooling calculation.

Because of the non-linear nature of the enthalpy-wet bulb temperature relationship it is not possible to derive a closed form numerical integration equation such as equation (8). Instead, an iterative scheme was used in which h* and h are first based on the water temperature and wet bulb air temperature at the faces of the element where fluid is entering. The two temperatures at the mid-point of the element are then taken as the mean of the influent and effluent temperatures and the numerical integration is repeated. This process is continued until the two exit temperatures converge within a tolerance of 0.01 degrees F. This iterative procedure is described more fully in Appendix I.

The computation of the temperature changes within the tower are made just ahead of the ammonia stripping calculations in order that the Henry's Law constant can be recomputed for each element of the tower based on the average temperature for the element.

The details of how to use the program for crosscurrent cooling tower calculations or ammonia stripping calculations are given in the section of the report entitled HOW TO USE THE PROGRAM.

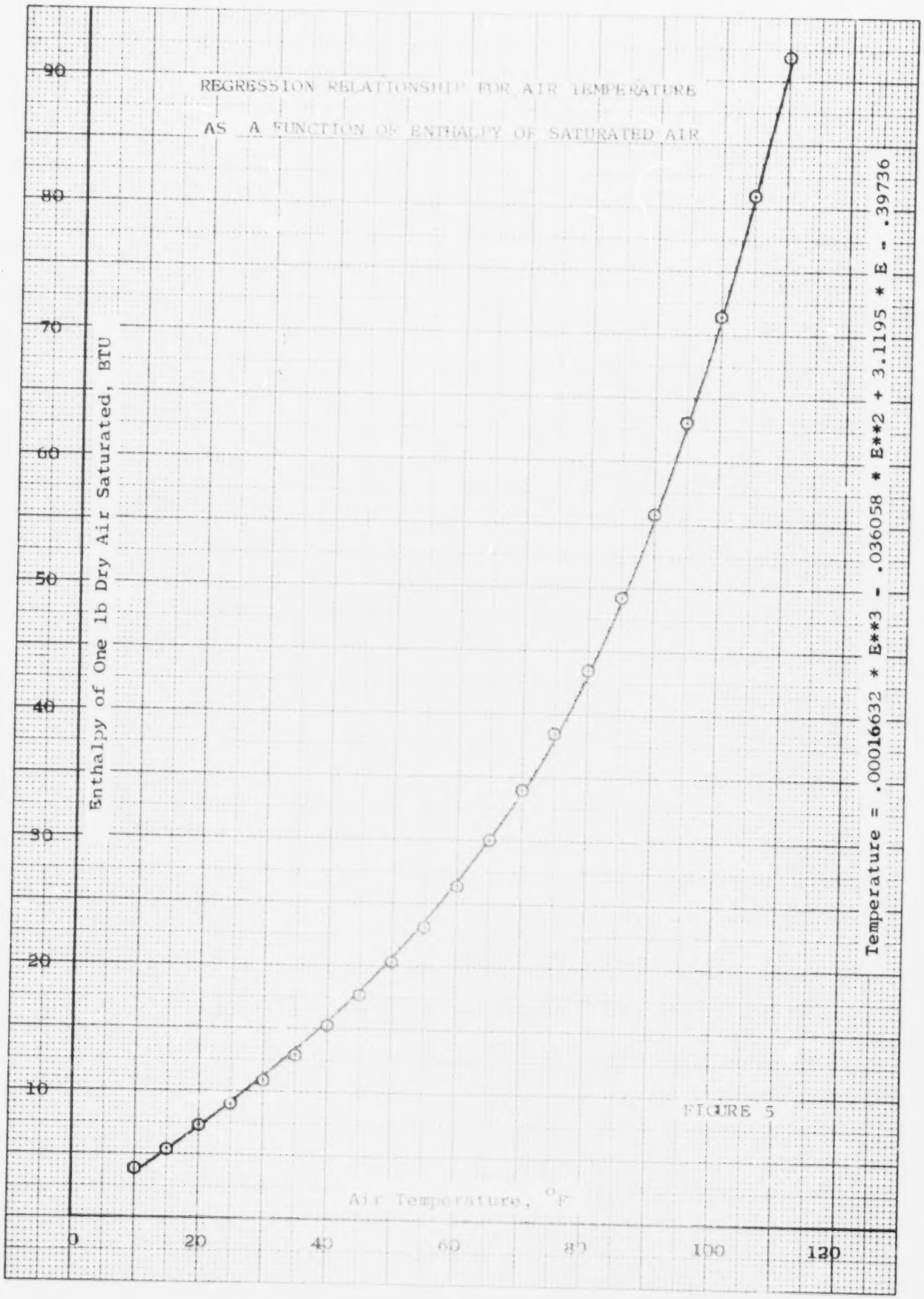

REGRESSION RELATIONSHIP FOR AIR TEMPERATURE
AS A FUNCTION OF ENTHALPY OF SATURATED AIR
Temperature = .00016632 * E**3 - .036058 * E**2 + 3.1195 * E - .39736
Enthalpy of One lb Dry Air Saturated, BTU
Air Temperature, °F
0
20
40
60
80
100
120
10
20
30
40
50
60
70
80
90

FIGURE 5

COUNTERCURRENT TOWERS

Referring to Figure 1 we see that the tower element for the countercurrent case is a horizontal slice one foot deep, dz in height and having a one square foot horizontal area. The mass balance relationship for ammonia can, therefore, be written as follows:

$$G'(y_j - y_{j+1}) = L'(x_j - x_{j+1}) \tag{12}$$

The rate of mass transfer for ammonia is expressed as follows:

$$y_j - y_{j+1} = (1/H_a)(y^* - y)dz \tag{13}$$

If y and y* are again taken as the mean values across the increment, the following closed form integration can be derived:

$$y_{j+1} = y_j - \frac{\left[2mx_j - (1 + R)y_j\right] dz/H_a}{1 + (R - 1)dz/H_a} \tag{14}$$

where $R = mG/L$

The conservation of energy equation for countercurrent towers is written as follows:

$$G\,(h_j - h_{j+1}) = L\,(T_j - T_{j+1}) \tag{15}$$

The rate of energy transfer for countercurrent towers is expressed by the following equation:

$$h_j - h_{j+1} = (1/H_t)(h^* - h)dz \tag{16}$$

As in the crosscurrent case, these equations cannot be solved in closed form using the "Modified Euler" Method. An iterative method described in Appendix I was used.

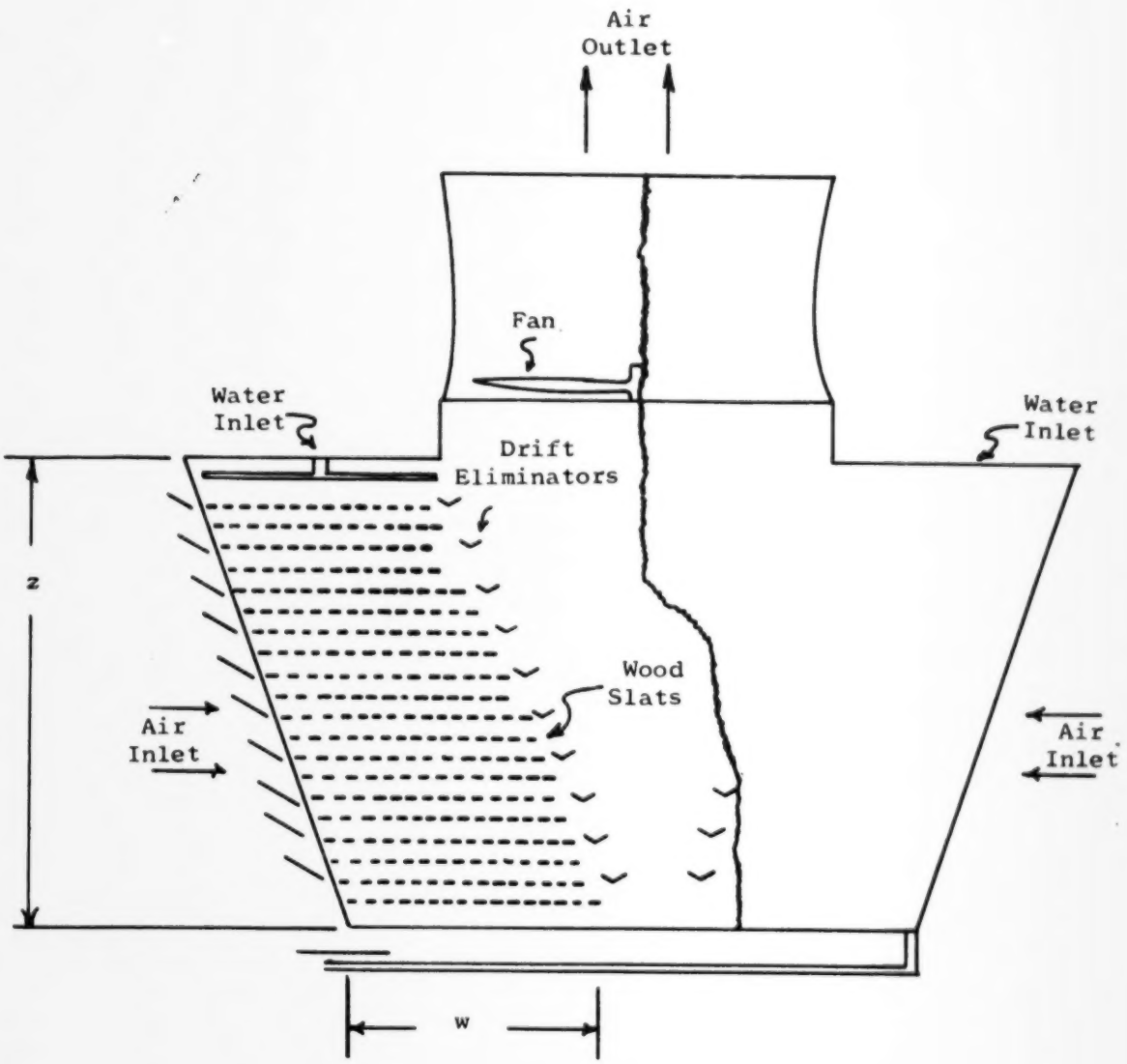
The countercurrent tower is solved from the top down. The wet bulb temperature of the air leaving the tower is not known at the beginning of the calculation. It is, therefore, necessary to guess at the effluent wet bulb temperature. It is known that the effluent wet bulb air temperature cannot be greater than the influent water temperature and cannot be less than the wet bulb temperature of the air entering the tower. Using these two limits; the first guess for the wet bulb temperature of the effluent air is half way between the influent water temperature and the wet bulb temperature of the influent air. The calculation then proceeds down the column until the ammonia concentration in the leaving water is equal to or less than the target value supplied as input. When the calculation is terminated, the temperature of the air entering the last element must equal the input temperature for influent air. If the computed air temperature does not agree with the input value within a tolerance of 0.01 ^{o}F, a new value for wet bulb temperature of effluent air is selected by means of Bolzano's method[9] and the whole tower calculation is repeated. This iterative process is continued until the computed influent air temperature equals the input value within the tolerance. For countercurrent towers good results have been obtained using a value of 0.25 ft for dz.

Relationships for computing pressure drop in both kinds of towers were taken from Kelly and Swenson[10]. The pressure drop which is directly proportional to the air density times the square of the air velocity is discussed fully in the section of this report entitled EMPIRICAL PRESSURE DROP RELATIONSHIPS.

EMPIRICAL MASS AND ENTHALPY TRANSFER RELATIONSHIPS

There have been extensive experimental studies of mass transfer relations to ammonia-water systems for counterflow towers, using particle and grid packing. However, very little data is available for crossflow towers using film type packing. No published data is available for mass transfer on the special coated wood slats used at Tahoe[11]. The packing used at Tahoe is schematically represented in Figure 6. The computer program simulates this type of crossflow tower which is symmetrical about a vertical plane. At Tahoe the horizontal and vertical spacing is so close that the packing may be assumed to be of the film type. Since in ammonia stripping of wastewater the pH is very high (10.5), the packing (wood slats) must be specially treated to prevent lignification. The use of plastic media has been proposed but at this writing no data is available. The mass transfer relations found in the literature were obtained empirically from conventional packing. The approach taken to find the proper mass transfer relation was to consider several in calculating the height of the tower at South Tahoe based on the limited data available and then select what appeared to be the best fit. Finally, it was assumed that the mass transfer relations initially derived for counterflow towers were applicable to crosscurrent towers.

Johnstone and Singh[12] studied film packing constructed of wood grids and developed an overall gas phase mass transfer coefficient as a function of the gas loading rate for sulfur dioxide. This was converted to ammonia transfer by multiplying by the ratio of diffusivities to the 2/3 power. G was varied from 1000 to 5000 lbs/hr/sq ft while L was held constant at 1080 lbs/hr/sq ft. The relationship for NH_3 is



Schematic Representation of
Packing Arrangement in
Tower at Tahoe

FIGURE 6

$$K_g A_p = 1.5\ V_o\ G^{.8}\ A_p$$

$$H_a = \frac{.023\ G^{.2}}{V_o\ A_p}$$

where

K_g = gas mass transfer coefficient, lb moles/(hr)(sq ft)(atm)

A_p = the specific surface area, sq ft/cu ft

G = air loading rate, lb/hr/sq ft

V_o = a constant that varies with the nature of the packing approximately about .005

H_a = Height of overall gas phase transfer unit for ammonia, ft

Molstad[13] et al studied wood grids and developed an overall gas phase mass transfer coefficient as a function of the gas and liquid loading rates. They considered decks constructed of wood slats 4 inches high, 1/4 inch thick and spaced 5/8 inch apart (Figure 7). For some measurements 1/2 inch legs between decks were added. The liquid rate, L, varied from 1800 to 18000 lb/hr sq ft and the gas rate varied from 100 to 1100 lb/hr sq ft. The mass transfer coefficient (without legs) was empirically found to be

$$K_g\ A_p = .00215(G)^{.63}(L)^{.59}$$

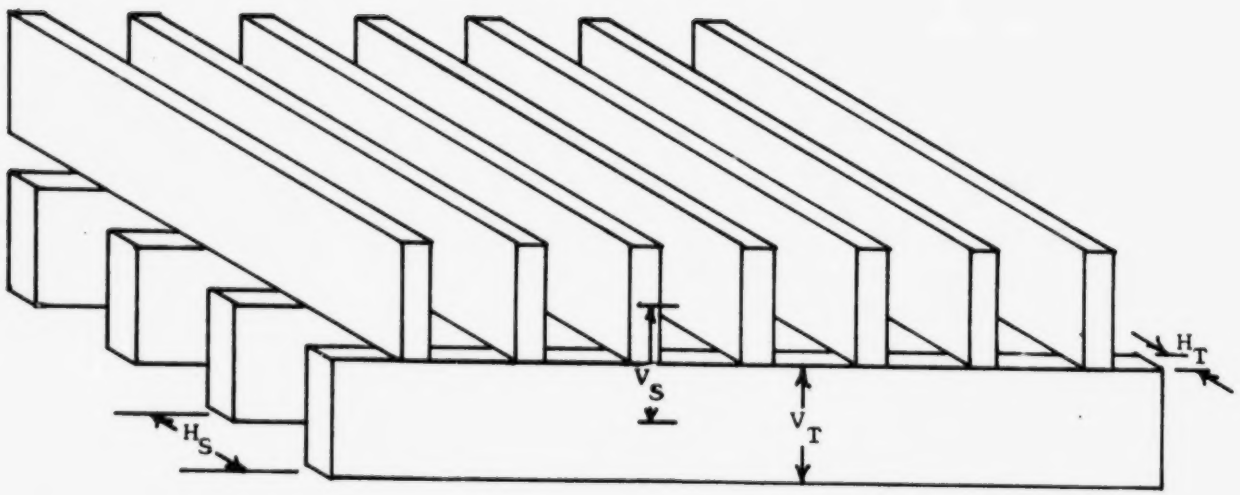
$$H_a = 16.03G^{.37}/L^{.59}$$

and with legs

$$K_g\ A_p = .011\ G^{.57}L^{.26}$$

$$H_a = 3.135G^{.43}/L^{.26}$$

where L = liquid loading rate, lb/hr/sq ft



Schematic of Grid Packing

FIGURE 7

Although initially many of the studies were predicated on the assumption that the system was gas phase controlling, recent studies[6] using particle packing have indicated that the liquid phase may provide from 5 to 40 percent of the resistance at 25°C. Due to the lack of data it would be difficult to check this for film packing. For particulate packing the height of a liquid transfer unit alone was determined by Onda, Sada and Murase[14]. This height coupled with the height of a gas phase transfer unit measured by Sherwood and Holloway[15] yields an overall height of a gas phase transfer unit. Onda, Sada and Murase's equation are derived from Higbie's penetration theory and a dimensional analysis scheme.

It has already been stated that special treatment of the packing is required. This special treatment consists of a special coating of neoprene on the wood slats or perhaps using plastic media. In either case the wettability of the packing is reduced and the nature of the surface of the packing approaches particle packing. Onda, Sada and Murase's equation considers the effect of specific surface and as a consequence may be applied to film packed ammonia stripping towers. The relationships are as follows:

$$H_g = 1.01G^{.31}/L^{.33}$$

$$H_L = \left[\frac{\mu^2}{\rho^2 g}\right]^{1/3} \frac{1}{.021} \left[\frac{L}{A_p \mu}\right]^{.51} \left[\frac{\mu}{\rho D}\right]^{.5}$$

$$H_a = H_g + H_L \left[\frac{G'm}{L'}\right]$$

where

H_g = height of gas phase transfer unit, ft

H_L = height of liquid phase transfer unit, ft

H_a = overall height of gas phase transfer unit, ft

m = Henry's law constant, dimensionless

μ = viscosity of water, lb/ft hr

ρ = density of water, lb.cu ft

g = acceleration of gravity, 4.17×10^8 ft/hr^2

D = diffusivity in the liquid phase, sq ft/hr

The viscosity of water was obtained from the expression by Hazen[16]

$$\mu = \frac{78.6(2.42)}{(T + 10)}$$

where T is the temperature of the water, ^oF

Both the density of water and the diffusivity of ammonia in water were taken from data and equations given in Perry's Handbook[6]. In estimating the density of water, the density of the vapor was neglected and the density of the water was increased by a factor of 1.025 to account for the dissolved salts present in the wastewater. The relationships are

$$\rho = 7.4275(705.39 - T)^{1/3}$$

$$D = 3.154 \times 10^{-7}(460 + T)/\mu$$

where T is the temperature of the water in ^oF.
The density of water at 68^o F (20^o C) was used as a reference.

Finally, if the packing is in wood slats, then the specific surface area is

$$A_p = 24(H_T + V_T)/(H_S \cdot V_S)$$

where

H_T = horizontal thickness, in.

V_T = vertical thickness, in.

H_S = horizontal spacing, in.

V_S = vertical spacing, in.

The three mass transfer relations are illustrated in Figure 8 by plotting the height of a transfer unit versus the gas loading rate at two liquid loading rates. The Molstad relation differs considerably from both Sherwood and Johnstone and Singh.

Some data were obtained from the operating tower at South Tahoe[17]. Based on these data the tower heights were calculated using both the Molstad and the combination of Sherwood and Onda et al. The results are tabulated in Table I.

One problem at Tahoe is the continued precipitation of calcium carbonate on the wooden slats resulting in a loss of efficiency. Since the packing height is 24 feet, it would seem reasonable to conclude that the performance of the tower can be more readily demonstrated by the relation of Sherwood, Onda et al. Although the results of the Johnstone and Singh relations compare favorably with the Sherwood-Onda et al, it was decided to use the latter because only when the work of Onda et al and Sherwood et al are combined is the liquid phase resistance and the temperature considered.

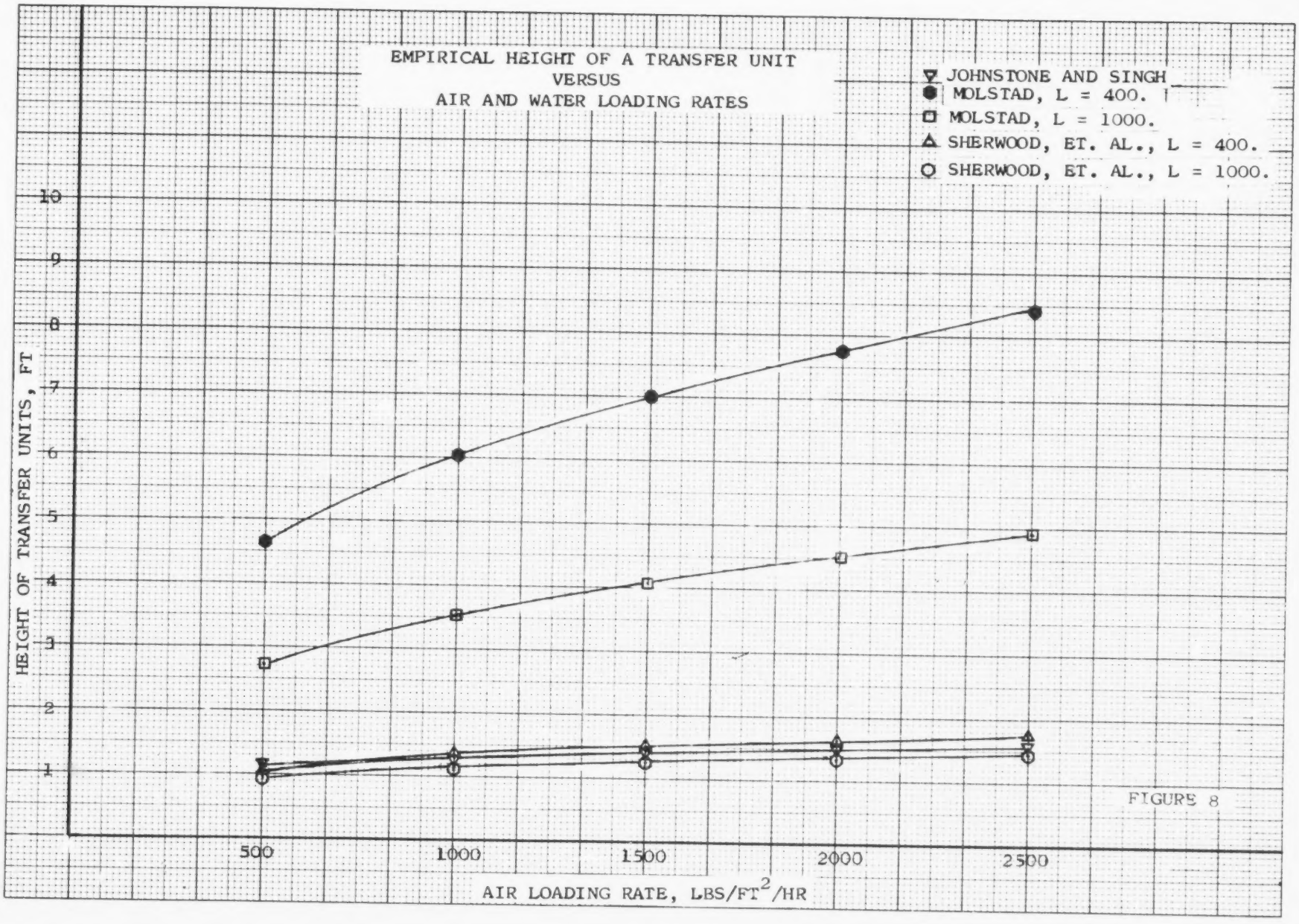

EMPIRICAL HEIGHT OF A TRANSFER UNIT
VERSUS
AIR AND WATER LOADING RATES
JOHNSTONE AND SINGH
MOLSTAD, L = 400.
MOLSTAD, L = 1000.
SHERWOOD, ET. AL., L = 400.
SHERWOOD, ET. AL., L = 1000.
HEIGHT OF TRANSFER UNITS, FT
10
9
8
7
6
5
4
3
2
1
500
1000
1500
2000
2500
AIR LOADING RATE, LBS/FT^2/HR

FIGURE 8

TABLE I

COMPARISON OF MASS TRANSFER RELATIONS

NH_3 conc., mg.l		Flow, MGD	L $lb/hr/ft^2$	G $lb/hr/ft^2$	Height	
INF.	EFF.				Molstad	Sherwood, Onda et al
16.4	3.6	1.6	620	2480	31	19
19.6	6.9	2.1	813	2280	23	17
20.8	4.7	1.8	698	2346	31	20
18.2	8.7	3.0	1162	2053	21	19

In the literature cooling tower enthalpy transfer relationships for film packings are equated with various packing arrangements. Obviously, a more general relationship would have included all the relations into one equation with the specific surface area as the distinguishing factor. By using the data of Wood and Betts[18] and the equations of Lowe and Christie[19], the mass transfer coefficients were obtained for various known specific surfaces and L and G. These data were then plotted (Figure 9) versus the specific surface area and least squares regression was applied. The result was

$$K_a = .00624\ L\ A_p \left[\frac{G}{L}\right]^{.7}$$

and

$$H_t = \frac{160.25}{A_p}\left[\frac{L}{G}\right]^{.3}$$

where

K_a is enthalpy transfer coefficient and

H_t is the height of an enthalpy transfer unit

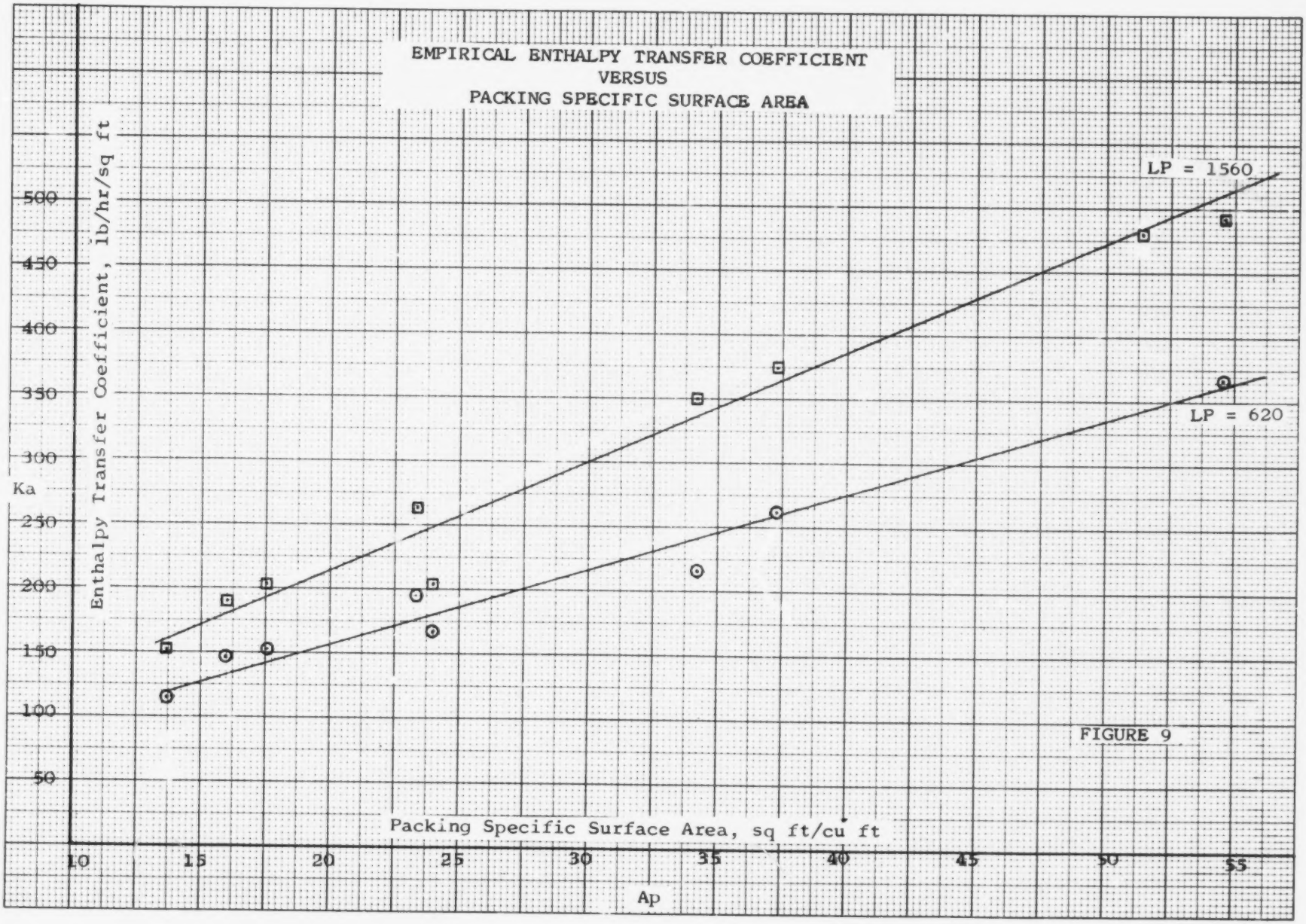

EMPIRICAL ENTHALPY TRANSFER COEFFICIENT
VERSUS
PACKING SPECIFIC SURFACE AREA
Enthalpy Transfer Coefficient, lb/hr/sq ft
Ka
500
450
400
350
300
250
200
150
100
50
LP = 1560
LP = 620
Packing Specific Surface Area, sq ft/cu ft
10
15
20
25
30
35
40
45
50
55
Ap

FIGURE 9

EMPIRICAL PRESSURE DROP RELATIONSHIPS

For the counterflow tower with film packing the air pressure drop was obtained from the correlation of Johnstone and Singh[12].

$$\Delta P = f \cdot z \cdot G^{1.8}$$

Where f is a Fanning friction factor and is tabulated in Table II and z is packing height as illustrated in Figure 6.

In the case of the crossflow tower using film packing, relationships for computing pressure drop were taken from Kelly and Swenson[10]. The air pressure drop is composed of two parts: The first due to the obstruction of the packing and the second to the free falling drops of water. Kelly and Swenson's relations deal with splash packed countercurrent cooling towers. The most significant difference between splash and film packing is that film packing is more compact. But since no correlations for film packed crossflow towers were found, the Kelly and Swenson relations were used assuming that the smallest vertical packing correlation was equivalent to film packing.

Consequently, in a crossflow tower air enters at the sides and meets the obstructions in the same manner as if the tower were counterflow. That is, the crossflow tower is simply the counterflow tower rotated 90° for purposes of pressure drop calculation. The pressure drop caused by the filling and support member (obstructions) is then,

$$\Delta P_1 = 12\alpha \cdot G^2 \cdot w/H_S \left[\frac{.0675}{\rho_g}\right]$$

where

w = width of tower (parallel to air flow), ft

α = constant

H_S = horizontal spacing as illustrated in Figure 7, inches

TABLE II

FRICTION FACTORS FROM VARIOUS WOOD GRIDS

DIMENSION OF GRIDS

$V_T = V_S$	H_S	$f \times 10^8$
1	.625	18.9
2	.625	13.7
4	.625	8.3
8	.625	5.7
4	1.25	2.43
8	1.25	1.79
12	1.25	1.20
4	1.75	1.73
8	1.75	1.16
12	1.75	.95
4	2.25	.87
8	2.25	.68
12	2.25	.63

V_T = vertical thickness, inches

V_S = vertical spacing, inches

H_T = horizontal thickness, 0.025 inches

H_S = horizontal thickness, inches

f = Fanning friction factor

The free falling drops of water pass through the tower at right angles to the air flow. Again, recalling a 90° rotation the pressure drop caused by the water is

$$\Delta P_2 = \frac{.0012\beta\ S_F^{\frac{1}{2}}\ L\ G_E^{\ 2}\ z}{V_S} \left[\frac{.0675}{\rho_g}\right]$$

where β = constant

G_E is the equivalent air mass velocity.

$$G_E = \sqrt{G^2 + 4800\ G\rho_g\ (64.4\ S_D)^{\frac{1}{2}} + 32.2(3600\ \rho_g)^2\ S_F}$$

The vertical free fall of a water drop, S_F, is approximated by

$$S_F = \frac{V_S\ H_S}{12\ H_T}$$

The density of the air depends principally on the dry bulb temperature. The dry bulb temperature, however, is not given as an input to the program. Instead, the wet bulb temperature of the air is used. The error introduced is small. Take for example, air at 100°F dry bulb and 10% relative humidity. The wet bulb temperature would then be 63°F. The error in air density would be (460 + 100)/(460 + 63) or 7%. Since the dry bulb temperature is always greater than the wet bulb temperature, the greatest wet bulb temperature within the tower is used to compute air density. For the crosscurrent tower this corresponds to the air discharged from the first row of elements.

ρ_g is the density of air and given as .0808 lbs/cu ft at 0°C and one atm. The density is corrected for temperature variation at the outlet wet bulb temperature, T_g.

$$\rho_g = \frac{.0808 \times 492}{(T_g - 460)}$$

To simulate the crossflow film packed tower from Kelly and Swenson, α is selected as $.26 \times 10^{-8}$ and β is $.07 \times 10^{-8}$. The total pressure drop is

$$\Delta P = \Delta P_1 + \Delta P_2$$

COST ESTIMATION

The capital cost data for the fan was obtained from several suppliers. The cost data was combined and a least squares regression fit was obtained. The cost was increased by a factor of 1.45 to account for field installation. The following relationship was found for fan cost:

$$\text{Cost of Fan, dollars} = .01175\left[\frac{G \cdot A_c \cdot \Delta P}{\rho_g \cdot E_f}\right]^{.824}$$

where

G = air rate, lbs/hr/sq ft

A_c = area perpendicular to the direction of air flow, sq ft

ΔP = pressure drop, in. of H_2O

ρ_g = density of air, lbs/cu ft

E_f = efficiency of fan, dimensionless

The pump equipment cost was obtained from data by Guthrie[20]. The equipment cost represents the sum of the cost of the pump plus the cost of the motor. To obtain the total investment the equipment cost was multiplied first, by a field installation factor and second, by a base module cost factor to account for such items as labor for excavation, foundation work, field labor and materials, and contractor's indirect costs. These data were then fitted by regression to the following equation:

$$\text{Cost of Pumps, dollars} = 986.9\left[\frac{Q \cdot z}{E_p}\right]^{.44} + 37.95(Q \cdot z)^{.97}$$

where

Q = the liquid flow, mgd

z = tower height, ft

E_p = efficiency of the pump, dimensionless

The first term is the cost of the pump and the second term is the cost of the motor. The efficiency of the motor was taken as 60%.

The supporting structure of the tower contains little steel because of corrosion problems. However, pressure treated hemlock is, roughly comparable to steel in cost. Consequently, the cost of the supporting structure of the tower was developed from medium open steel structure data presented by Guthrie[20]. A regression analysis of his data resulted in the following equation:

$$\text{Cost of Structure, dollars} = 1.177 \cdot s \cdot w \cdot z^{1.462}$$

where

s = length of tower, ft

w = width of tower, ft

z = height of tower, ft

The width given above is only for the counterflow tower. For the crossflow tower symmetrical about a vertical plane (Figure 6), the width was taken as 3.5 times the packing width. A 34% increase was allowed for field installation.

The external coverings of the tower and the lighting and electrical work were also obtained from Guthrie's data. The external coverings were taken from an average process building. The low cost range was chosen for lighting and electrical work. A 15% and a 30% increase were added on both costs for contingencies and building subcontract. The resulting equation was

$$\text{Exterior and Electrical Cost, dollars} = 29.95 \cdot s \cdot w$$

The water distribution system was also taken from Guthrie's data using the minimum values. The cost of distribution in dollars is $11800 \cdot Q$.

The cost of the fill was calculated from data supplied by N. W. Kelly[21] and then updated to account for special treatment to retard deterioration of the wood by the logic of Snow and Whek[23]. Therefore, the cost of solid fill is estimated at $\$6.00/ft^3$ of wood (C_w) or loose fill is

$$\text{Cost of Packing, dollars} = \frac{1.45 \cdot C_w \cdot V_T \cdot H_T}{V_s \cdot H_s}$$

where

V_T = vertical thickness of wood slat, in.

H_T = horizontal thickness of wood slat, in.

V_s = vertical spacing between wood slat, in.

H_s = horizontal spacing between wood slat, in.

A factor of 1.45 was included for field installation.

The horsepower required to pump the liquid is

$$\frac{L(z+1)s \cdot w}{1{,}980{,}000\ E_p}$$

where

L = the liquid rate, $lbs/hr/ft^2$

The term, $z+1$, provides for the liquid to be distributed one foot above packing height, z. The horsepower required to move the air is

$$\frac{0.000002626 \cdot \Delta P \cdot G \cdot s \cdot w}{\rho_g \cdot E_f}$$

The annual cost of electrical power for the fan is equal to the unit power cost, C_k, in cents per kilowatt hour times the fan horsepower times a conversion factor of 6532. Thus, fan power is given by the following relation:

$$\text{Fan Power Cost, dollars/yr} = \frac{.01715 \cdot \Delta P \cdot G \cdot s \cdot w \cdot P_c \cdot C_k}{\rho_g \cdot E_f}$$

P_c is the fraction of time the tower is operating per year. Similarly, the annual cost of the pump power is given as follows:

$$\text{Pump Power Cost, dollars/yr} = \frac{.003298 \cdot L \cdot s \cdot w \cdot (z+1) \cdot P_c \cdot C_k}{E_p}$$

According to McKelvey and Brooke[22] for cooling towers the cost of chemicals (algacides, fungicides, and wood preservatives) is equal to the cost of electrical power. Labor and supplies represent about 12% of the electrical power cost. Thus, the cost of chemicals, labor, and supplies is 1.12 times the cost of electrical power. It was assumed that these costs will apply to ammonia stripping towers.

The capital costs were amortized at two different rates, AMF1 and AMF2. Both factors may be read into the program, AMF1 deals with packing and structure and as an example is amortized at 5.0% for 20 years to give a factor of .08024. AMF2 is concerned with the fan and pump costs. A typical factor is for 15 years at 5% or .09634. The program also prints out cost data in terms of cents per thousand gallons.

The FWPCA Construction Cost Index, CCI, was used to update the data to June 1968. For future use, CCI may be read into the program and all the capital cost data will be updated.

HOW TO USE THE PROGRAM

The program can be used in four different ways for simulating:

1) crossflow ammonia stripping towers; set TYPE = 0, TE = 0, CLOUT = desired exit concentration of ammonia in the liquid.
2) counterflow ammonia stripping towers; set TYPE = 1, TE = 0, CLOUT = desired exit concentration of ammonia in the liquid.
3) crossflow cooling towers; set TYPE = 0, TE = desired exit temperature of the liquid.
4) counterflow cooling towers: set TYPE = 1, TE = desired exit temperature of the liquid.

When the program is used for a stripping tower, the entering concentration of ammonia in the liquid (CLINP) and the desired exit concentration of ammonia in the liquid (CLOUT), which are supplied to the program as input, form the basis of the iteration to calculate the dimensions of the tower necessary to achieve the desired reduction in liquid concentration. The numerical integration is carried out using DELZ size increments. Costs and other information relating to the tower are also calculated and printed out.

When the program is used for a cooling tower, the entering temperature of the liquid (TH20) and the desired exit temperature of the liquid (TE), which are supplied as input to the program, form the basis of the iteration to calculate the dimensions of the tower necessary to achieve the desired reduction in the liquid temperature. The numerical integration is carried out using DELZ size increments. Costs and other information relating to the tower are also calculated

and printed out. When using the program for cooling tower calculations, it is not necessary to supply input values for CLINP and CLOUT.

In using the program, it has been noted that a DELZ integration interval of one foot is adequate for simulating a crossflow stripping or cooling tower. Using a smaller interval will give a little better accuracy, but the difference is trivial. Also using an integration interval of less than a foot (such as 1/4 of a foot) for a crossflow tower greatly increases the computing time. To simulate a crossflow stripping tower 14 feet wide by 20 to 30 feet high takes about 45 seconds of running time on an IBM 1130 computer using a 1 foot integration interval.

For a counterflow stripping or cooling tower, a DELZ integration interval of .25 feet is adequate. Using a smaller interval, however will not affect the computing time nearly as much as in the cross-flow case. To simulate a counterflow stripping tower of about 20 feet with DELZ = .25 feet takes about 45 seconds on the IBM 1130 computer.

Each input case to the program consists of 3 data cards containing 25 variables, as described in Table III and Figure 10. The program may print out several error messages that suggest various problems with the input. The program will always print something for each case, since it is not possible for the program to get caught in a loop. The following are the error messages:

1) CROSSFLOW TEMPERATURE ITERATION DOES NOT CONVERGE

The exit liquid temperature from a DELZ increment within the tower cannot be calculated by means of enthalpy changes across the increment.

TABLE III

INPUT DATA CARDS FOR THE PROGRAM

Input Card 1:	FORMAT (I2) NCASE
Input Card 2:	FORMAT (8F10.3) CLINP, CLOUT, TH2O, TWB, GP, LP, W, DELZ
Input Card 3:	FORMAT (8F10.3) HTH, VTH, HS, VS, TE, Q, AMF1, AMF2
Input Card 4:	FORMAT (2E10.2,5F10.3,F9.3,I1) ALPHA, BETA, EF, EP, PCTIM, CKWH, CPA, CCI, TYPE
Input Card 5:	Start over with Input Card 2 to begin next case.

See Figure 10

```
    .66E-6      .70E-9   .75      .75       .96       .008      6.        1.        0
1.375       .375        8.       1.5       40.       1.6       .08       .096
16.4        3.8         51.2     32.       2412.84   619.64    14.       1.
```

COOLING TOWER INPUT FORM

```
2,,,
```

2) CROSSFLOW TOWER HEIGHT EXCEEDS 400 DELZ

The program has calculated up to this tower height and the demand liquid concentration (or demand temperature) has not yet been achieved. Increase the DELZ increment size or raise the CLOUT value (or TE value).

3) COUNTERFLOW TOWER HEIGHT EXCEEDS 400 DELZ

The program has calculated up to this tower height and the demand liquid concentration (or demand temperature) has not yet been achieved. Increase the DELZ increment size or raise the CLOUT value (or TE value).

4) CONCENTRATION OF LIQUID FAILS TO DECREASE DOWN THE TOWER

The ammonia concentration of the liquid does not decrease when calculated through a DELZ increment. This indicates the GP is too low to remove any ammonia from the liquid. This comment refers only to a counterflow tower.

5) COUNTERFLOW TEMPERATURE ITERATION DOES NOT CONVERGE

The exit wet bulb temperature (TAIR) necessary to satisfy the system does not lie between TWB and TH2O. This is an invalid situation.

6) TOWER INOPERABLE BECAUSE OF ICING

The exit temperature of the liquid has dropped below the freezing point, and the tower cannot operate under freezing conditions.

A flow diagram for the program is shown in Figure 11.

LOGICAL FLOW DIAGRAM FOR DIGITAL COMPUTER PROGRAM

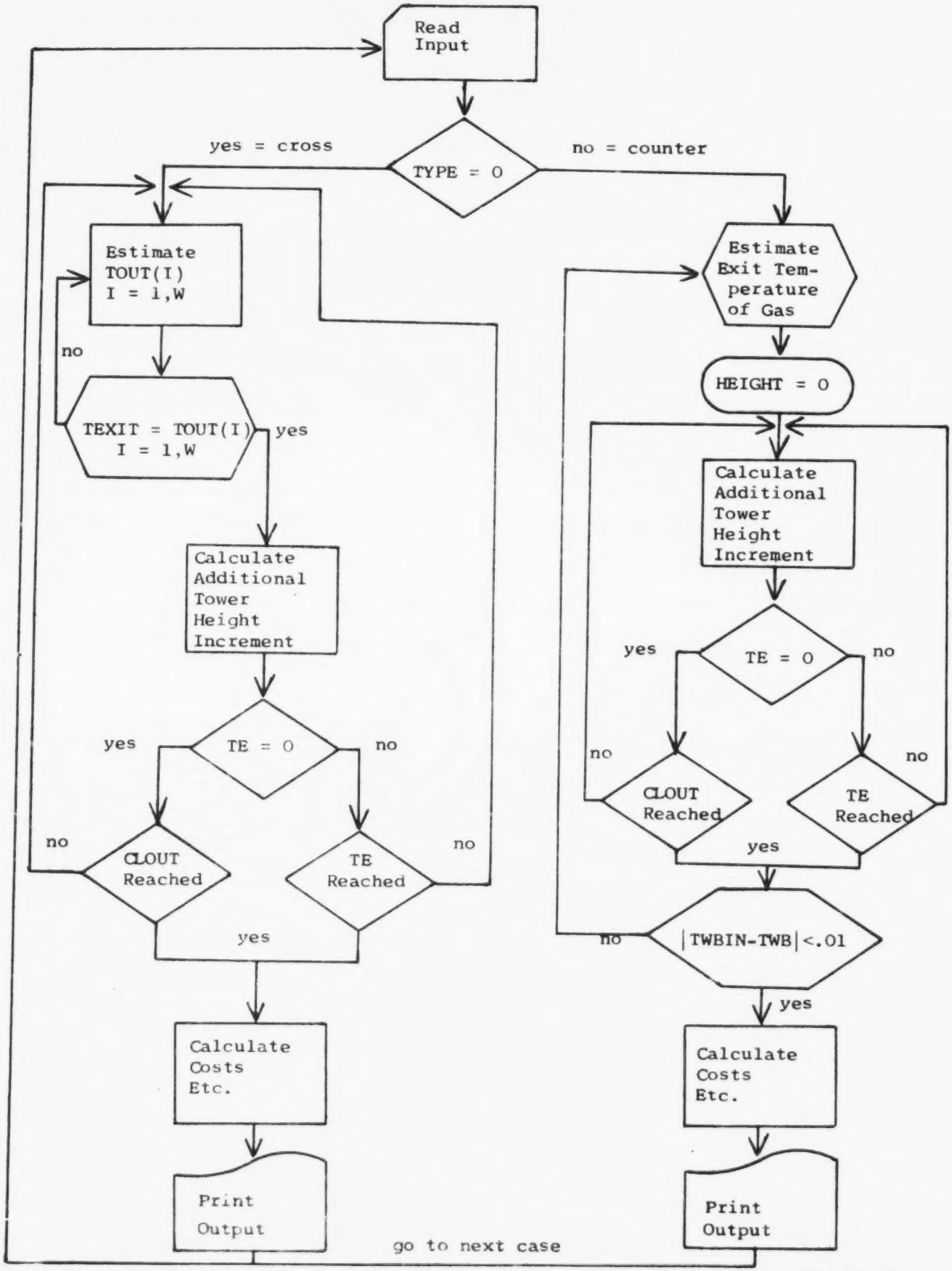


FIGURE 11

COMPUTED RESULTS

In order to draw some conclusions about the ammonia stripping and cooling tower model, the interplay of several variables was observed using the program, and a graphical analysis of these results is shown in Figures 12 to 17. Data taken at Lake Tahoe was used as the design point for the calculations, and summer operating conditions were assumed, i.e., TH20 = 70°F and TWB = 60°F. The variables observed were height of the tower, precent of ammonia removal, volume flow, total treatment cost, and the gas loading rate to liquid loading rate ratio. Flow, G/L, and percent removal are the quantities that were permitted to vary in the system.

Three graphs were drawn to represent the computed output for the crossflow ammonia stripping tower. Figure 12 shows the relationship between the percent removal and the height of the tower at various G/L values. Figure 13 shows the relationship between the G/L ratio and the total treatment cost at various levels of percent removal. Note that the optimum total treatment cost occurs around a G/L value of 2. Based on this value of G/L = 2, Figure 14 shows the relationship between the volume flow and the total treatment cost at various levels of percent removal. Note that the total treatment cost levels off between 7 to 10 mgd.

Similarily, three graphs were drawn to represent the computed output for the counterflow ammonia stripping tower. Figure 15 shows the relationship between the percent removal and the height of the tower at various G/L values. Figure 16 shows the relationship between the G/L ratio and the total treatment cost at various levels

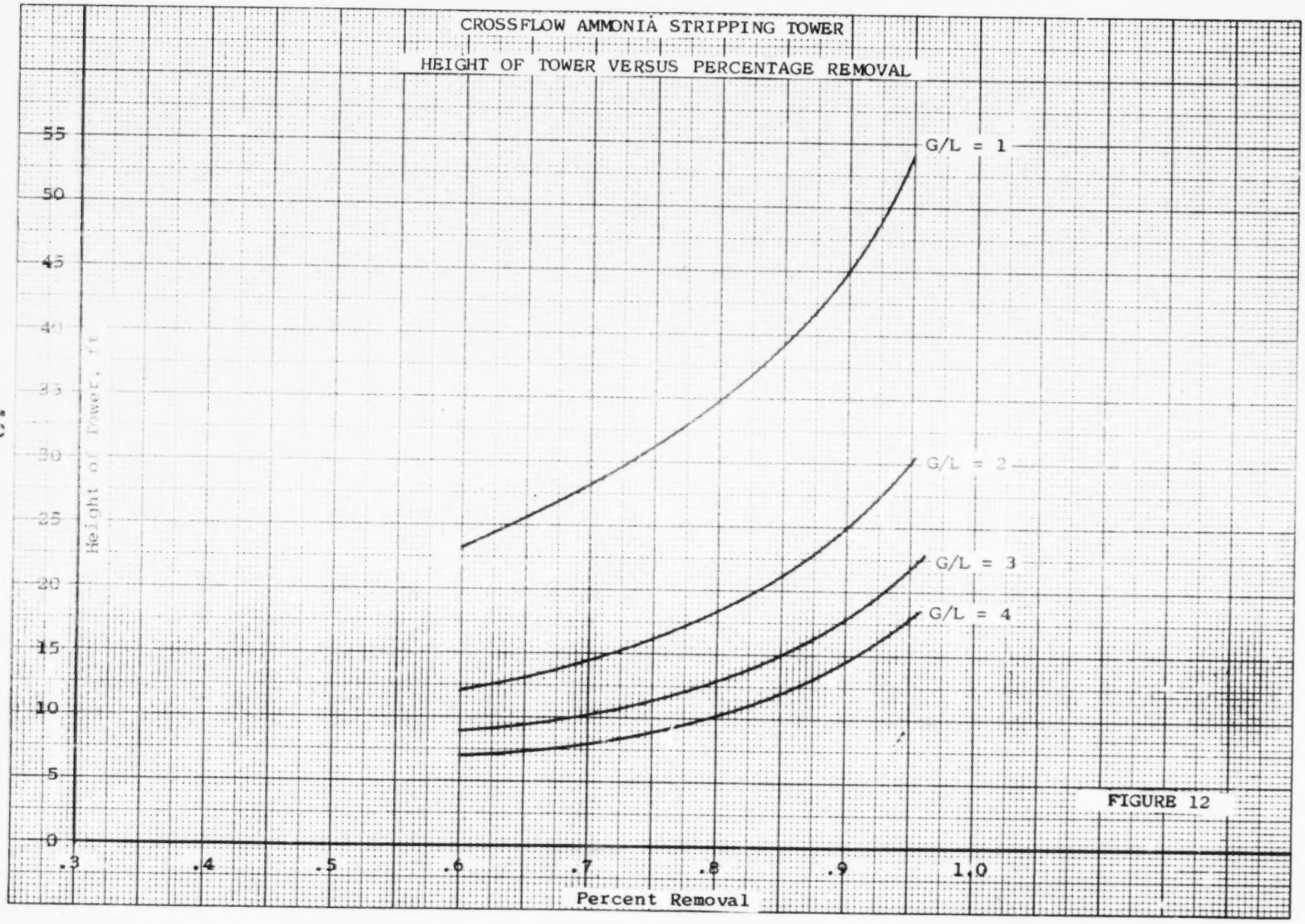

CROSSFLOW AMMONIA STRIPPING TOWER
HEIGHT OF TOWER VERSUS PERCENTAGE REMOVAL
G/L = 1
G/L = 2
G/L = 3
G/L = 4
55
50
45
40
35
30
25
20
15
10
5
0
.3
.4
.5
.6
.7
.8
.9
1.0
Percent Removal

FIGURE 12

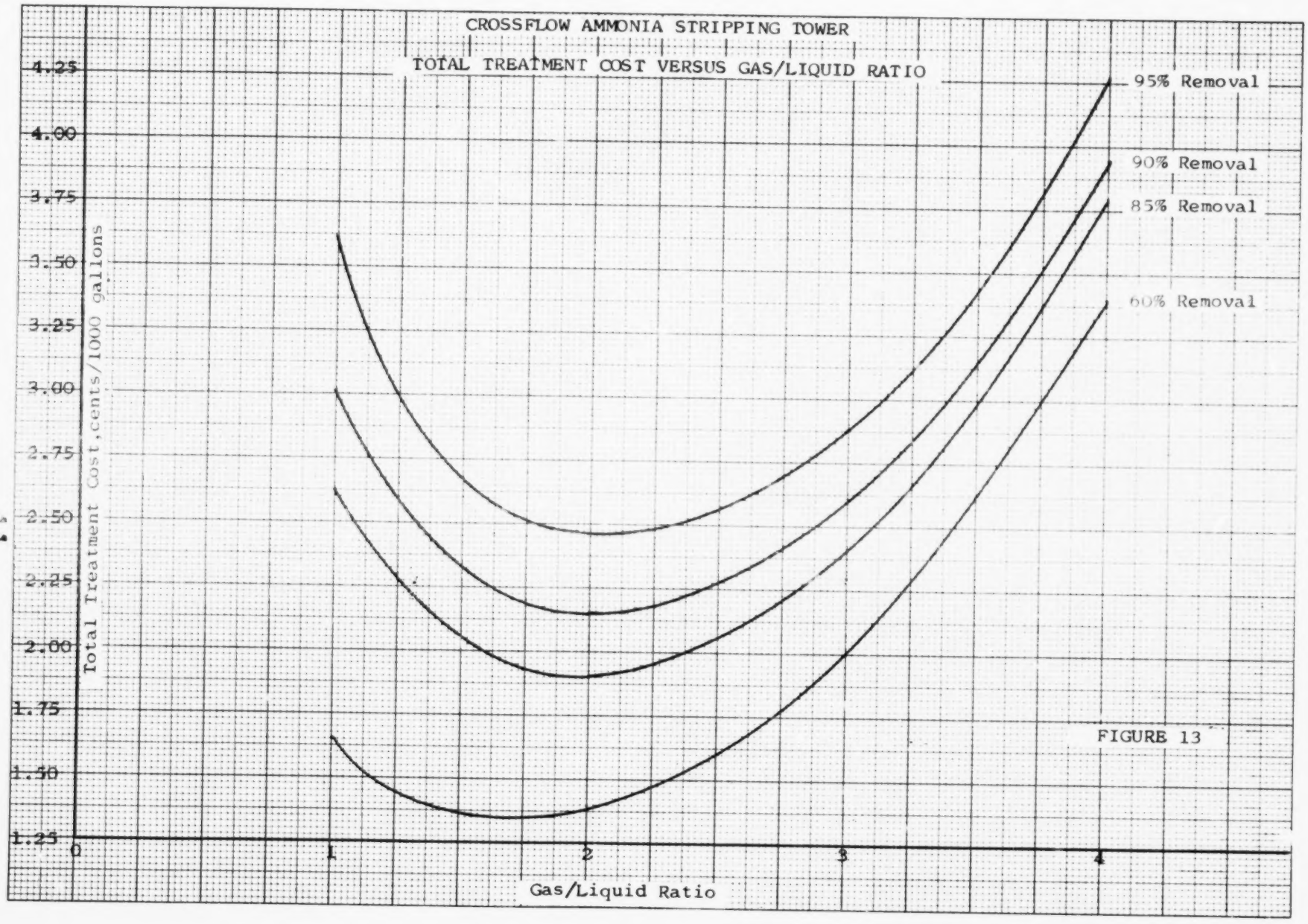

CROSSFLOW AMMONIA STRIPPING TOWER
TOTAL TREATMENT COST VERSUS GAS/LIQUID RATIO
95% Removal
90% Removal
85% Removal
60% Removal
Total Treatment Cost, cents/1000 gallons
4.25
4.00
3.75
3.50
3.25
3.00
2.75
2.50
2.25
2.00
1.75
1.50
1.25
0
1
2
3
4
Gas/Liquid Ratio

FIGURE 13

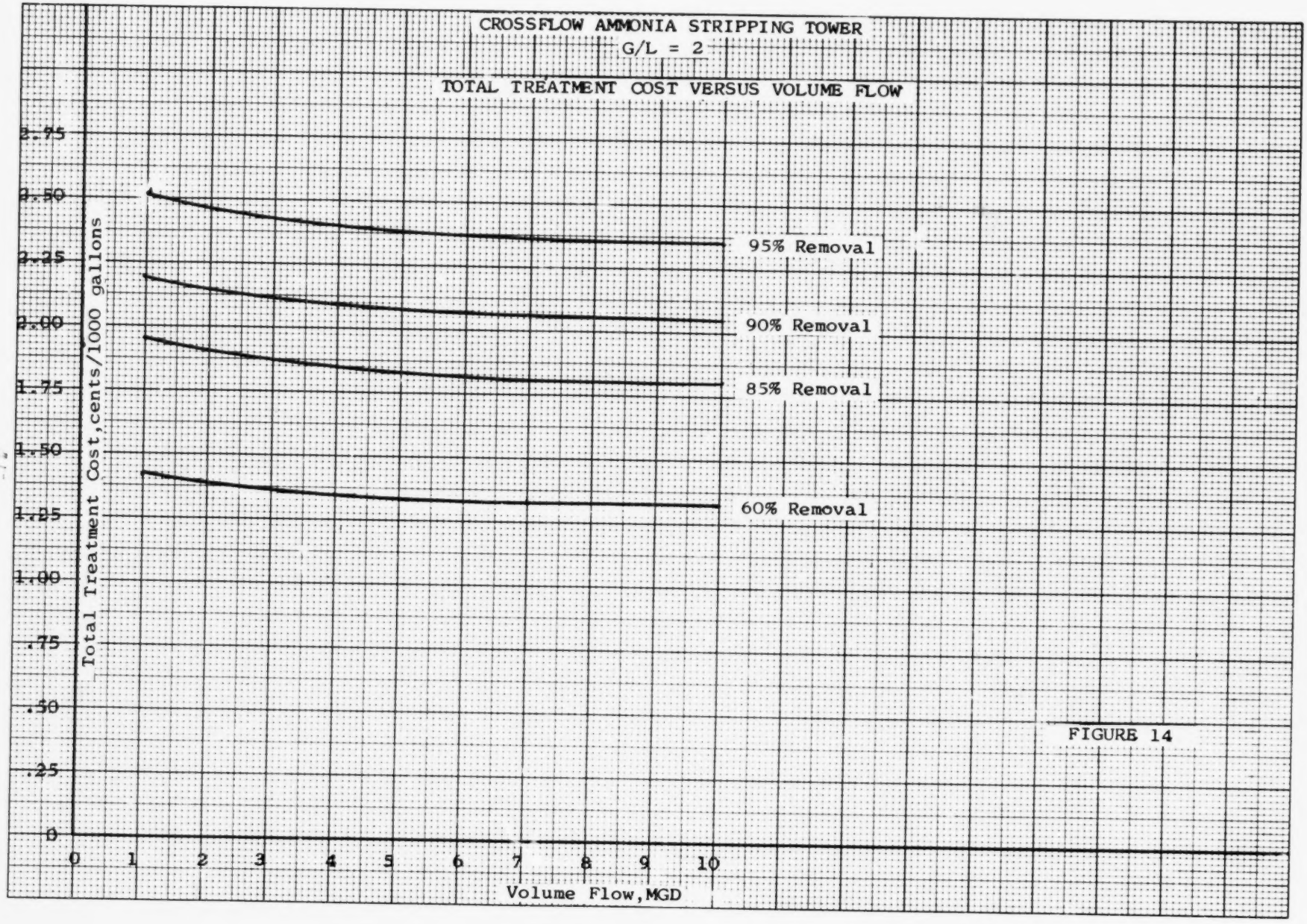

CROSSFLOW AMMONIA STRIPPING TOWER
G/L = 2
TOTAL TREATMENT COST VERSUS VOLUME FLOW
Total Treatment Cost, cents/1000 gallons
2.75
2.50
2.25
2.00
1.75
1.50
1.25
1.00
.75
.50
.25
0
95% Removal
90% Removal
85% Removal
60% Removal
0
1
2
3
4
5
6
7
8
9
10
Volume Flow, MGD

FIGURE 14

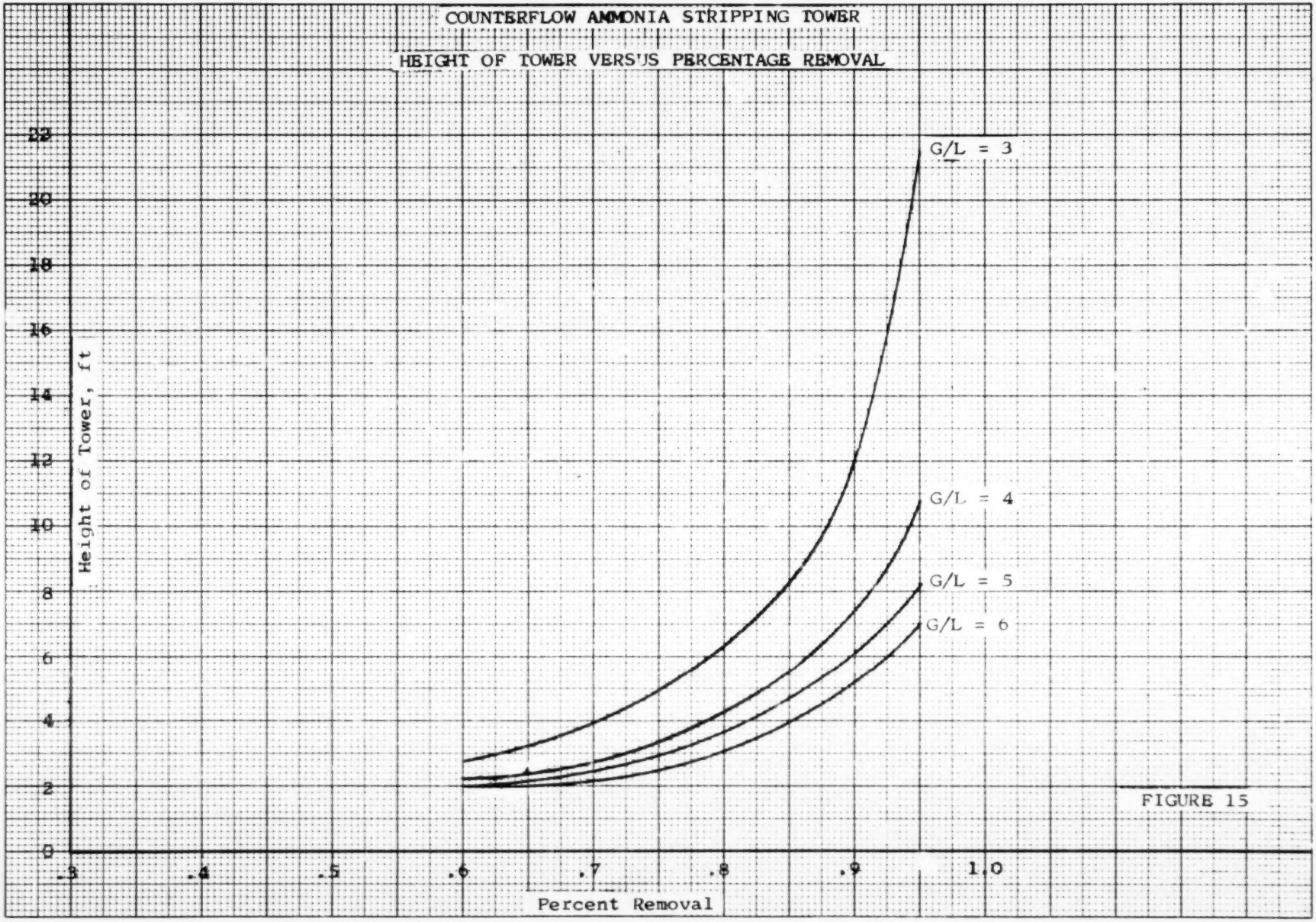

COUNTERFLOW AMMONIA STRIPPING TOWER
HEIGHT OF TOWER VERSUS PERCENTAGE REMOVAL
Height of Tower, ft
22
20
18
16
14
12
10
8
6
4
2
0
G/L = 3
G/L = 4
G/L = 5
G/L = 6
.3
.4
.5
.6
.7
.8
.9
1.0
Percent Removal

FIGURE 15

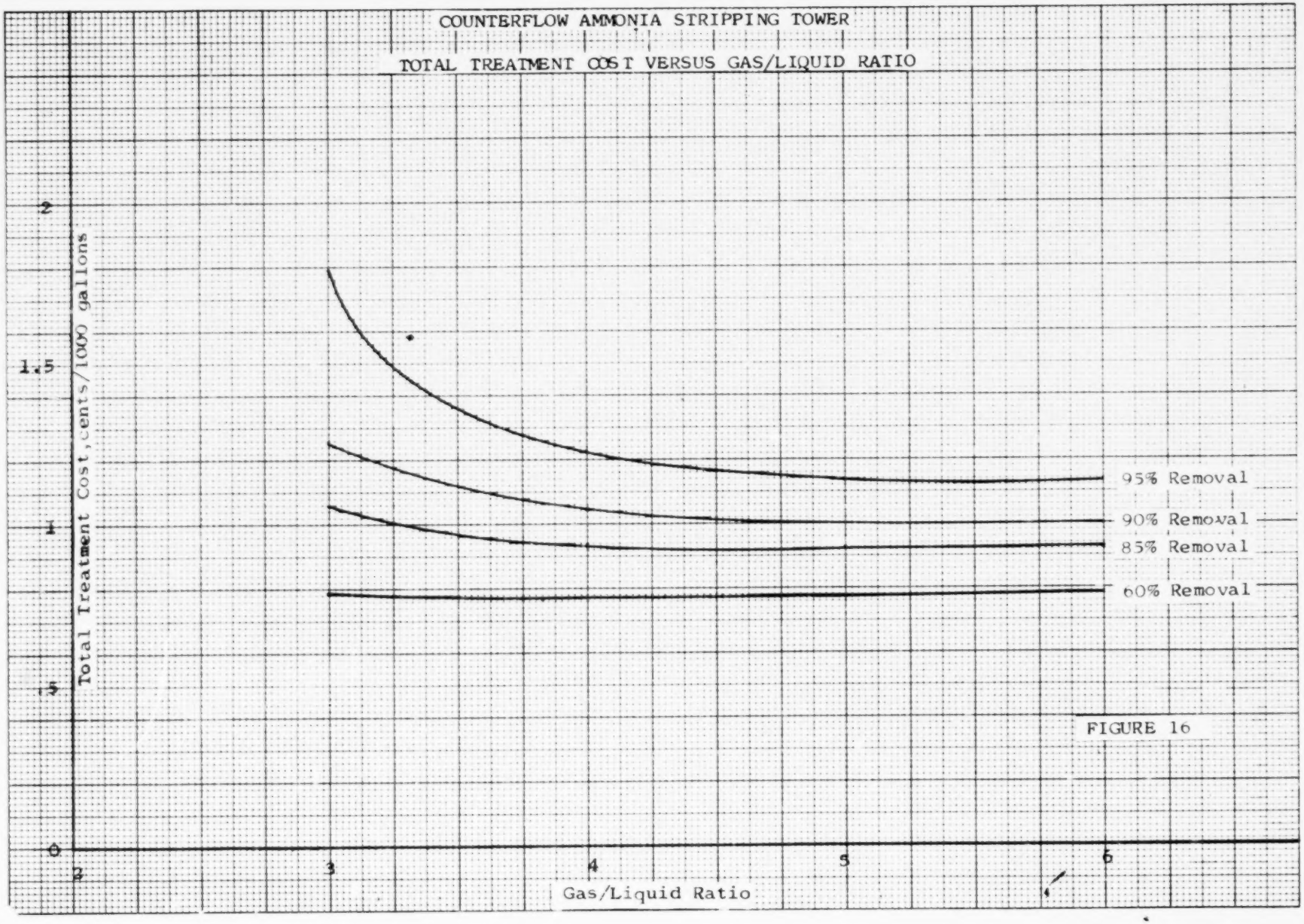

COUNTERFLOW AMMONIA STRIPPING TOWER
TOTAL TREATMENT COST VERSUS GAS/LIQUID RATIO
Total Treatment Cost, cents/1000 gallons
2
1.5
1
.5
0
2
3
4
5
6
Gas/Liquid Ratio
95% Removal
90% Removal
85% Removal
60% Removal

FIGURE 16

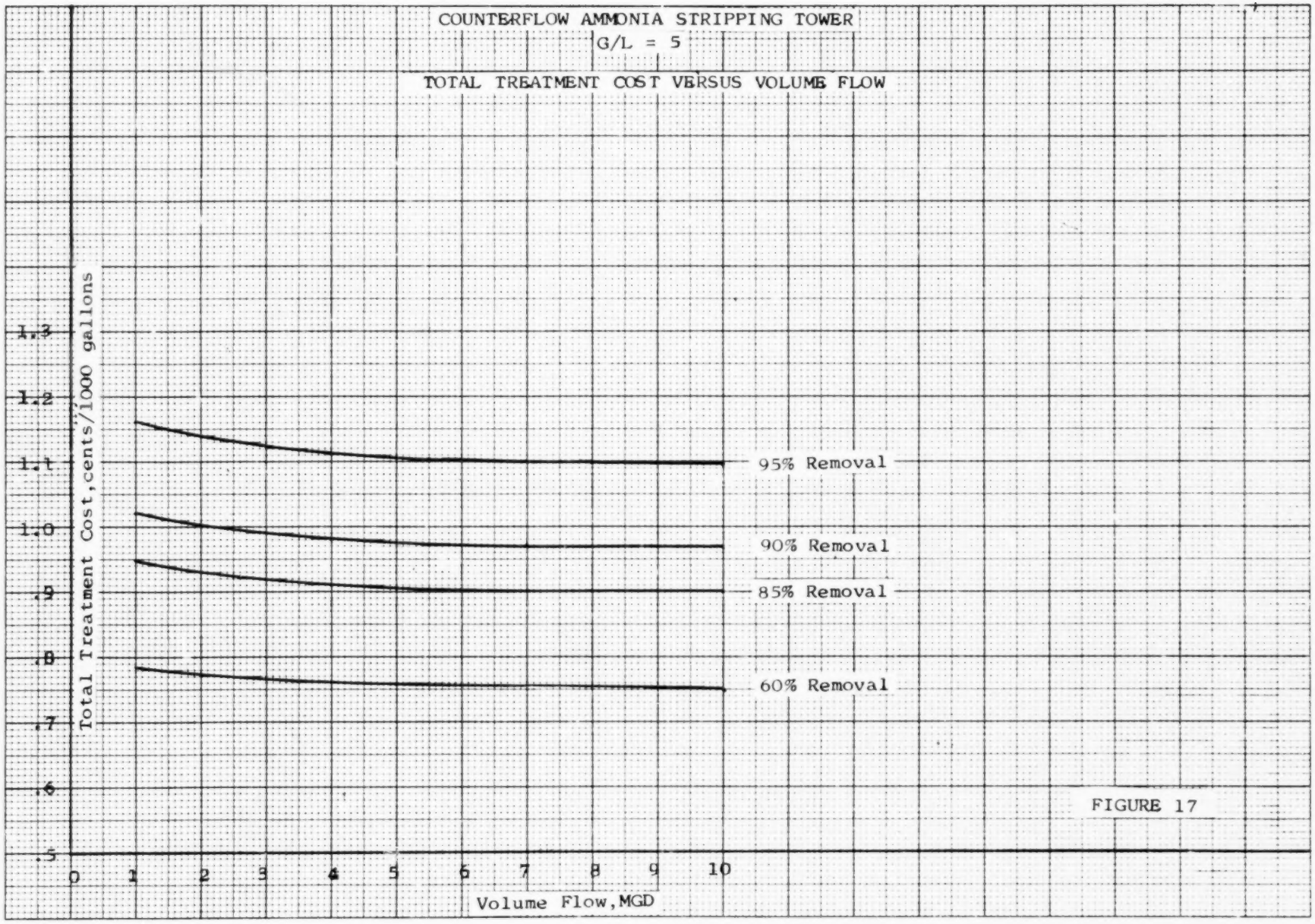

COUNTERFLOW AMMONIA STRIPPING TOWER
G/L = 5
TOTAL TREATMENT COST VERSUS VOLUME FLOW
Total Treatment Cost, cents/1000 gallons
1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
0
1
2
3
4
5
6
7
8
9
10
Volume Flow, MGD
95% Removal
90% Removal
85% Removal
60% Removal

FIGURE 17

of percent removal. It is not obvious from the graph, but an optimum total treatment cost is achieved around a G/L value of 5. Based on this value of G/L = 5, Figure 17 shows the relationship between the volume flow and the total treatment cost at various levels of percent removal. Note that the total treatment cost levels off between 7 and 10 mgd.

Similar graphical analysis could be made for both the crossflow and counterflow stripping towers assuming winter operating conditions, i.e., TH20 = 50^{o}F and TWB = 32^{o}F.

Figures 4 and 5 show the relationship between the enthalpy of one pound of dry air saturated and the air temperature in ^{o}F. By means of an IBM polynomial fitting computer program, the two relationships (temperature = f(enthalpy) and enthalpy = f(temperature)) were derived for temperatures between 10 and 110^{o}F. The plotted points are the table values, and the plotted curve is the polynomial fit. Both relationships are used in the stripping and cooling tower iterations.

Figure 2 shows graphically the relationship between mole fractions of NH_3 in water and mole fractions of NH_3 in air at various temperatures.

Figure 3 shows the relationship between temperature in degrees F and Henry's Law Constant. A linear least squares fit is also plotted on the graph.

CONCLUSIONS AND PLANS FOR ADDITIONAL WORK

The digital computer program presented in this report is intended first, as a tool for correlating experimental measurements on ammonia stripping towers used to treat wastewater and second, as a computational aid for the process design engineer or the water resource planner. Before the program can be used with confidence for design, the empirical mass and enthalpy transfer relationships as well as the pressure drop relationships must be available to the designer. This kind of data, as well as cost estimates, will usually be supplied by the tower manufacturer. At present, very little specific information for existing packings is available in the open literature. FWPCA has a continuing program to gather and correlate data from pilot plant and full-sized towers using the program as a correlation tool. Empirical relationships presented in this report are intended only for illustrative purposes and for order of magnitude computations.

The program is also deficient because it neglects secondary phenomena such as adsorption of carbon dioxide from ambient air which often results in scale formation and deterioration of the packing due to exposure to high pH water. Biological activity within the tower as well as adsorption of atmospheric oxygen are other factors not included which might be of importance for some applications. Plans exist to expand the present program to include these phenomena as more experimental data become available.

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APPENDIX I

DETAILS OF ITERATION SCHEMES IN COMPUTER PROGRAM

CROSSFLOW TEMPERATURE ITERATION

The entering liquid temperature to each DELZ size increment in the first horizontal row of a crossflow tower is TH20, which is supplied as input to the program. The entering liquid temperature to each increment in the second horizontal row is the exit liquid temperature from its corresponding increment in the first horizontal row, and so on down the tower. Each horizontal row consists of W (which is input to the program) DELZ size increments. The program continues adding rows of width W*DELZ and height DELZ, until the desired exit concentration of the liquid is achieved (or until the desired exit temperature of the liquid is achieved in the case of cooling towers).

The exit temperatures (TOUT(I),I=1,W) of the liquid from each incremental horizontal block in a row across the tower is unknown. Each horizontal block is iterated on, one at a time, to calculate its TOUT(I). When the iteration is completed for a block, the next horizontal block is iterated on, and so forth.

Let us consider a single block to illustrate how its exit liquid temperature (TOUT) is calculated by the program iteration. The program makes an initial estimate for the average temperature of the block (TAVG) by setting it equal to the entering liquid temperature (T) of the block, which is known from either input (TH20) or has been previously calculated by the program as the TOUT from the corresponding block in the previous horizontal row. The program also makes an initial estimate of the exit liquid temperature of the block by setting $TOUT_1$ equal to the entering

liquid temperature (T). An initial estimate of the average enthalpy of the air (HAVG) is made by setting it equal to the entering enthalpy (H_1) for the block. The enthalpy change across the block (DELH) is calculated from TAVG, the width of the block (DELZ), and the temperature height of the transfer unit. The exit enthalpy, $H_2 = H_1 + DELH$, and the temperature change across the block, DELT = GP/LP*DELH, are calculated. The program can now calculate the temperature of water leaving the block as, $TOUT_2 = T - DELT$. If the absolute value of ($TOUT_1 - TOUT_2$) is less than .01° F, the iteration is complete, and the program proceeds to the next block in the row and so on. If the tolerance is not satisfied, the program calculates a new TAVG = $(T + TOUT_1)/2$ and a new HAVG = $(H_1 + H_2)/2$, sets $TOUT_1 = TOUT_2$, and performs another calculation for a new $TOUT_2$. This process keeps repeating until the tolerance is satisfied.

If the iteration fails to converge after 10 passes, an error comment is printed, and the program proceeds to execute the next case.

COUNTERFLOW TEMPERATURE ITERATION

The exit wet-bulb temperature of the air (TAIR) from the counter-flow tower is unknown; so an initial estimate of $TAIR_1 = (TH2O+TWB)/2$ is made by the program, since TWB < TAIR < TH2O. The program then proceeds to calculate down the tower in DELZ size increments, until the desired exit ammonia concentration of the liquid is achieved (or until the desired exit temperature of the liquid is achieved, in the case of cooling towers). A value TWBIN is calculated based on the exit enthalpy at the bottom of the tower. TWBIN is the entering wet-bulb temperature of the gas that is necessary to satisfy the system that we have calculated based on the original estimate TAIR. TWBIN is compared to the actual entering wet-bulb temperature TWB, which is supplied to the program as input. If the absolute value of (TWBIN - TWB) is less than $.01^{\circ}F$, the iteration is complete and the program proceeds on. If the tolerance is not satisfied, the program must determine a better estimate for TAIR and perform the calculations again.

To do this, a Bolzano or "halfing" iteration is performed on the interval (TH2O - TWB), since the value of TAIR that satisfies the system must lie somewhere within this temperature range. If the tolerance was not satisfied and (TWBIN - TWB) is negative, then the original $TAIR_1$ estimate was too low, so the next estimate is one-half of the remaining upper interval, i.e, $TAIR_2 = (TH2O - TAIR_1)/2$. If the tolerance was not satisfied and (TWBIN - TWB) is positive, then the original $TAIR_1$ estimate was too high, so the next estimate is

one-half of the remaining lower interval, i.e., $TAIR_2 = (TAIR_1 - TWB)/2$. This type of iteration is repeated until the tolerance is satisfied.

If, however, the temperature iteration does not converge after 20 passes, an error comment is printed, and the program proceeds to the next case.

APPENDIX II

FORTRAN LISTING AND SAMPLE OUTPUT

FROM THE DIGITAL COMPUTER PROGRAM

```
      INTEGER TYPE
      REAL LP,LHTU,L,LENTH,LAM
      DIMENSION CLIN(41),TCUT(41),T(41),CL(41),CG(41),H(41)
      IN=2
      IC=5
      READ(IN,5) NCASE
    5 FORMAT(I2)
      DO 1000 III=1,NCASE
      READ(IN,10) CLINP,CLOUT,TH2O,TWB,GP,LP,W,DELZ,HTH,VTH,HS,VS,
     . TE,Q,AMF1,AMF2,ALPHA,BETA,EF,EP,PCTIM,CKWH,CPA,CCI,TYPE
   10 FORMAT(8F10.3,/,8F10.3,/,2E10.2,5F10.3,F9.3,I1)
      NW=W
      DELW=DELZ
      L=347000.*Q
      AP=24.*(HTH+VTH)/(HS*VS)
      THTU=160.25/AP*(LP/GP)**.3
      GHTU=1.01*GP**.31/LP**.33
      GLR=GP/29./LP*18.
      CLINP=CLINP*18./17.
      CLOUT=CLOUT*18./17.
      IF(TYPE) 150,20,150
   20 DO 30 I=1,NW
      CL(I)=CLINP
      T(I)=TH2O
   30 TOUT(I)=TH2O
      H(1)=-1.62754+.54789*TWB-.0064*TWB**2+.00008*TWB**3
      CG(1)=0.
      J=0
   40 J=J+1
      AVGCL=0.
      DO 70 I=1,NW
      TAVG=T(I)
      HAVG=H(I)
      JJ=0
   50 TEXIT=TOUT(I)
      JJ=JJ+1
      HSTAR=-1.62754+.54789*TAVG-.0064*TAVG**2+.00008*TAVG**3
      DELH=1./THTU*(HSTAR-HAVG)*DELW
      H(I+1)=H(I)+DELH
      DELT=GP/LP*DELH
      TOUT(I)=T(I)-DELT
      HAVG=(H(I)+H(I+1))/2.
      TAVG=(T(I)+TOUT(I))/2.
      IF(ABS(TEXIT-TOUT(I))-.01) 60,55,55
   55 IF(JJ-10) 50,56,56
   56 WRITE(IO,57)
   57 FORMAT(1H1,///,10X,'CROSSFLOW TEMPERATURE ITERATION DOES NOT CONVE
     .RGE',///)
      GO TO 510
   60 VIS=78.6/(TAVG+10.)*2.42
      DENSW=7.4275*(705.39-TAVG)**.333
      DIFFW=.031541*.00001*(TAVG+460.)/VIS
      LHTU=63.73*VIS**.66*(LP/AP)**.51/(DENSW**1.17*DIFFW**.5)*.001
      HLC=.1117*EXP(.02612*TAVG)
      AHTU=GHTU+LHTU*HLC*GLR
      R=DELW/AHTU
      P=1./GLR
```

```
      CL(I)=(2.*P/R+P-HLC)/(2.*P/R+P+HLC)*CLIN(I)+2/(2.*P/R+P+HLC)*CG(I)
      CG(I+1)=CG(I)+P*(CLIN(I)-CL(I))
      AVGCL=AVGCL+CL(I)
   70 CONTINUE
      IF(J-1) 75,74,75
   74 TAIR=-.39736+3.1195*H(NW+1)-.036058*H(NW+1)**2+.00016632*
     . H(NW+1)**3
   75 AVGCL=AVGCL/NW
      AVGCG=CG(1)
      TLIQ=0.
      DO 78 I=1,NW
      AVGCG=AVGCG+CG(I+1)
   78 TLIQ=TLIQ+TOUT(I)
      AVGCG=AVGCG/(NW+1)
      TLIQ=TLIQ/NW
      DO 80 I=1,NW
      CLIN(I)=CL(I)
   80 T(I)=TOUT(I)
      IF(J-399) 110,90,90
   90 WRITE(IO,100)
  100 FORMAT(1H1,///,10X,'CROSSFLOW TOWER HEIGHT EXCEEDS 400 DELZ',///)
      GO TO 510
  110 IF(TE) 130,120,130
  120 IF(AVGCL-CLOUT) 140,140,40
  130 IF(TLIQ-TE) 140,140,40
  140 HT=DELW*J
      LENTH=L/(2.*W*LP)
      VOL=2.*W*HT*LENTH
      STRUC=VOL*HT**.462*.5885
      G=2.*GP*LENTH*HT
      RATIO=G/L
      RHOG=.0808*492./(TAIR+460.)
      SF=VS*HS/(HTH*12.)
      GE=(GP**2.+4800.*GP*RHOG*(64.*SF)**.5+32*(3600*RHOG)**2.*SF)**.5
      DELP=(ALPHA*GP**2.*W*12./HS+BETA*(SF)**.5*LP*(GE)**2.*HT*.0012/VS)
     . *.0675/RHOG
      GO TO 390
  150 TOP=TH2O
      TLOW=TWB
      TAIR=(TH2O+TWB)/2.
      ITER=0
  160 ITER=ITER+1
      CL(1)=CLINP
      CG(1)=1./GLR*(CLINP-CLOUT)
      T(1)=TH2O
      H(1)=-1.62754+.54789*TAIR-.0064*TAIR**2+.00008*TAIR**3
      HAVG=H(1)
      TAVG=T(1)
      J=0
  170 J=J+1
      HSTAR=-1.62754+.54789*TAVG-.0064*TAVG**2+.00008*TAVG**3
      DELH=1./THTU*(HSTAR-HAVG)*DELZ
      H(2)=H(1)-DELH
      DELT=GP/LP*DELH
      T(2)=T(1)-DELT
      HAVG=(H(1)+H(2))/2.
      TAVG=(T(1)+T(2))/2.
```

```
      VIS=78.6/(TAVG+10.)*2.42
      DENSW=7.4275*(705.39-TAVG)**.333
      DIFFW=.031541*.00001*(TAVG+460.)/VIS
      LHTL=63.73*VIS**.66*(LP/AP)**.51/(DENSW**1.17*DIFFW**.5)*.001
      AHTL=GHTU+LHTL*GLMR
      HLC=.1117*EXP(.02612*TAVG)
      GLMR=GLR*HLC
      CG(2)=(CG(1)-(2.*HLC*CL(1)-(1.+GLMR)*CG(1))*DELZ/2./AHTL)/
     . (1.+(GLMR-1.)*DELZ/2./AHTU)
      CL(2)=CL(1)+GLR*(CG(2)-CG(1))
      IF(J-399) 230,210,210
  210 WRITE(IC,220)
  220 FORMAT(1H1,///10X,'COUNTERFLOW TOWER HEIGHT EXCEEDS 400 DELZ',///)
      GO TO 510
  230 IF(TE) 235,240,235
  235 IF(T(2)-TE) 248,248,246
  240 IF(CL(1)-CL(2)) 242,244,244
  242 WRITE(IO,243)
  243 FORMAT(1H1,///,10X,'CONCENTRATION OF LIQUID FAILS TO DECREASE DOWN
     . THE TOWER',///)
      GO TO 510
  244 IF(CL(2)-CLOUT) 248,248,246
  246 CL(1)=CL(2)
      CG(1)=CG(2)
      H(1)=H(2)
      T(1)=T(2)
      GO TO 170
  248 TWBIN=-.39736+3.1195*H(2)-.036058*H(2)**2+.00016632*H(2)**3
      IF(ABS(TWBIN-TWB)-.01) 310,310,250
  250 IF(ITER-20) 280,260,260
  260 WRITE(IC,270)
  270 FORMAT(1H1,///,10X,'COUNTERFLOW TEMPERATURE ITERATION DOES NOT CON
     .VERGE',///)
      GO TO 510
  280 IF(TWBIN-TWB) 290,290,300
  290 TLOW=TAIR
      TAIR=TAIR+.5*(TUP-TLOW)
      GO TO 160
  300 TUP=TAIR
      TAIR=TAIR-.5*(TUP-TLOW)
      GO TO 160
  310 HT=DELZ*J
      AVGCL=CL(2)
      AVGCG=1./GLR*(CLINP-CLOUT)
      TLIQ=T(2)
      LENTH=(L/LP)**.5
      W=LENTH
      VOL=LENTH*W*HT
      STRUC=VOL*HT**.462*.3363
      G=GP*LENTH*HT
      RATIO=G/L
      RHOG=.0808*492./(TAIR+460.)
      DELP=ALPHA*GP**1.8*HT
  390 IF(TLIQ-32.) 400,400,420
  400 WRITE(IO,410) TLIQ
  410 FORMAT(1H1,///,10X,'TOWER INOPERABLE BECAUSE OF ICING, EXIT TEMPER
     .ATURE OF LIQUID =',F10.3,///)
```

```
      GO TO 510
  420 FAN=.343*(G/(RHOG*EF*60.)*DELP)**.824
      PUMP=986.9*(G*HT/EF)**.44+37.95*(G*HT)**.97
      PACK=1.45*CPA*VOL*VTH*HTH/(VS*HS)
      EXEL=29.25*W*LENTH
      DIST=11800.*G
      STRUT=STRUC+EXEL+DIST
      CAP=FAN+PUMP+PACK+STRUT*CCI
      ACEG=(AMF2*FAN+AMF2*PUMP+AMF1*PACK+AMF1*STRUT)*95.23/(L*PCTIM)*CCI
      FANPW=DELP*GP*L/(LP*RHOG*EF)*PCTIM*CKWH*.017154
      PUMPW=L*(HT+1.)/EP*PCTIM*CKWH*.003298
      LAM=(FANPW+PUMPW)*1.12
      OPER=FANPW+PUMPW+LAM
      OCEG=OPER*95.23/(L*PCTIM)
      ACPG=ACEG+OCEG
      IF(TYPE) 470,450,470
  450 WRITE(IO,460)
  460 FORMAT(1H1,//,52X,'CROSSFLOW TOWER')
      GO TO 500
  470 WRITE(IO,480)
  480 FORMAT(1H1,//,52X,'COUNTERFLOW TOWER')
  500 AVGCL=AVGCL*17./18.
      WRITE(IO,800) HT,TLIQ,W,RATIO,LENTH,DELP,VOL,AVGCL
      WRITE(IO,805) AVGCG
      WRITE(IO,810) FAN,FANPW,PUMP,PUMPW,PACK,LAM
      WRITE(IO,820) STRUT,OPER,CAP,OCEG,ACEG,ACPG
  510 CLINP=CLINP*17./18.
      CLOUT=CLOUT*17./18.
      WRITE(IO,830) G,CLINP,CLOUT,TH2O,LP,GP
      WRITE(IO,840)
      WRITE(IO,850) CKWH,AMF1,AMF2,ALPHA,BETA,PCTIM,TWB,EP,EF,TE
      WRITE(IO,860) VTH,HTH,TYPE,VS,HS,CPA,CCI,W,DELZ
  800 FORMAT(/  ,17X,'DIMENSIONS OF PACKING',48X,'OTHER DATA'///2X,'HEIG
     1HT (FT)',38X,F10.3,5X,'EXIT LIQUID TEMPERATURE',20X,F10.3,//2X,'WI
     2DTH (FT)',39X,F10.3,5X,'LBS AIR /LBS WATER',25X,F10.3//2X,'LENGTH
     3(FT)',38X,F10.3,5X,'PRESSURE DROP (IN OF H2O)',18X,F10.3//2X,'VOLU
     4ME (CU FT)',35X,F10.1,5X,'CONCENTRATION OF LIQUID OUT  (MG/L)',
     58X,F10.3,/)
  805 FORMAT(66X,'CONCENTRATION OF GAS OUT     (MG/L)',8X,F10.3,///)
  810 FORMAT(24X,'CAPITAL COSTS',37X,'ANNUAL OPERATING AND MAINTENANCE C
     1OSTS'///2X,'COST OF FAN ($)',34X,F10.2,5X,'COST OF FAN POWER PER Y
     2EAR ($)',13X,F10.2//2X,'COST OF PUMP ($)',33X,F10.2,5X,'PUMPING PO
     3WER COST PER YEAR ($)',12X,F10.2//2X,'PACKING COST ($)',33X,F10.2,
     45X,'CHEMICAL,LABOR,MAINTENANCE COST PER YEAR ($)',F9.2/)
  820 FORMAT(2X,'STRUCTURE COST ($)',31X, F10.2,5X,'TOTAL OPERATING COST
     1 PER YEAR ($)',10X,F10.2//2X,'TOTAL CAPITAL COST ($)',27X,F10.2,5X
     2,'OPERATING COST IN CENTS/1000 GALS',10X,F10.3,//2X,'DEBT SERVICE
     3 IN CENTS/1000 GALS',17X,F10.3///35X,'TOTAL COST IN CENTS/1000 GAL
     4S',2X,F10.3///)
  830 FORMAT(45X,'STREAM MATRIX INPUT DATA'//2X,'FLOW,MGD',4X,'NH3 IN',4
     1X,'NH3 OUT',3X,'TEMPERATURE OF ENTERING WATER',4X,'LIQUID LOADING
     2RATE    AIR LOADING RATE'/F9.3,3X,F8.3,2X,F8.3,13X,F8.3,18X,F10.2,
     3 13X,F10.2//)
  840 FORMAT(45X,'DECISION MATRIX INPUT DATA'//2X,'COST OF',6X,'AMORTIZA
     1TION FACTORS   ALPHA IN    BETA IN     PER CENT    WET BULB',4X, '
     2PUMP',8X,'FAN          COOLING'/2X,'ELECTRICITY',5X,'AMF1',7X,'AMF2
     3     PRESSURE    PRESSURE    TIME TOWER  TEMP        EFFICIENCY  E
```

```
     4FFICIENCY  TCWER'/2X,'$/KWH',31X,'DRCP EC.     DRCP EQ.    OPERATED
     5',16X,'FACTOR       FACTLR       EXIT TEMP')
  850 FCRMAT(F10.3,2F12.3,2E12.2,5F12.3)
  860 FORMAT(//2X,'VERTICAL',4X,'HORIZONTAL    TYPE', 6X,'VERTICAL    HO
     1RIZONTAL  CCST CF     CONSTRUCTION',3X,'TOWER    INCREMENT'/2X,'TH
     2ICKNESS   THICKNESS',15X,'SPACING OF  SPACING CF  SCLIC FILL  COST
     3 INDEX',5X,'WICTH    HEIGHT'/2X,'BARS,IN.    BARS,IN.',16X,'BARS,I
     4N.    BARS,IN.    $/CU.FT.    PHS',12X,'FT.       FT.'/F9.3,F12.3,
     5 I10,2X,4F12.3,2X,F12.3,F11.3)
 1000 CONTINUE
      CALL EXIT
      END
```

CROSSFLOW TOWER

DIMENSIONS OF PACKING

HEIGHT (FT)	18.000
WIDTH (FT)	14.000
LENGTH (FT)	32.000
VOLUME (CU FT)	16128.0

OTHER DATA

EXIT LIQUID TEMPERATURE	34.767
LBS AIR /LBS WATER	5.006
PRESSURE DROP (IN OF H2O)	1.115
CONCENTRATION OF LIQUID OUT (MG/L)	3.459
CONCENTRATION OF GAS OUT (MG/L)	0.775

CAPITAL COSTS

COST OF FAN ($)	27112.32
COST OF PUMP ($)	5901.51
PACKING COST ($)	24116.51
STRUCTURE COST ($)	68063.92
TOTAL CAPITAL COST ($)	125194.27
DEBT SERVICE IN CENTS/1000 GALS	1.883

ANNUAL OPERATING AND MAINTENANCE COSTS

COST OF FAN POWER PER YEAR ($)	5404.47
PUMPING POWER COST PER YEAR ($)	356.24
CHEMICAL,LABOR,MAINTENANCE COST PER YEAR ($)	6452.01
TOTAL OPERATING COST PER YEAR ($)	12212.73
OPERATING COST IN CENTS/1000 GALS	2.182

TOTAL COST IN CENTS/1000 GALS 4.065

STREAM MATRIX INPUT DATA

FLOW,MGD	NH3 IN	NH3 OUT	TEMPERATURE OF ENTERING WATER	LIQUID LOADING RATE	AIR LOADING RATE
1.600	16.399	3.600	51.800	619.64	2412.83

DECISION MATRIX INPUT DATA

COST OF ELECTRICITY $/KWH	AMORTIZATION FACTORS AMF1	AMF2	ALPHA IN PRESSURE DROP EQ.	BETA IN PRESSURE DROP EQ.	PER CENT TIME TOWER OPERATED	WET BULB TEMP	PUMP EFFICIENCY FACTOR	FAN EFFICIENCY FACTOR	COOLING TOWER EXIT TEMP
0.008	0.080	0.096	0.26E-08	0.70E-09	0.960	32.000	0.750	0.750	0.000

VERTICAL THICKNESS BARS,IN.	HORIZONTAL THICKNESS BARS,IN.	TYPE	VERTICAL SPACING OF BARS,IN.	HORIZONTAL SPACING OF BARS,IN.	COST OF SOLID FILL $/CU.FT.	CONSTRUCTION COST INDEX PHS	TOWER WIDTH FT.	INCREMENT HEIGHT FT.
0.375	1.375	C	1.500	2.000	6.000	1.000	14.000	1.000

COUNTERFLOW TOWER

DIMENSIONS OF PACKING

HEIGHT (FT)	10.500
WIDTH (FT)	72.790
LENGTH (FT)	72.790
VOLUME (CU FT)	55634.4

OTHER DATA

EXIT LIQUID TEMPERATURE		66.311
LBS AIR /LBS WATER		0.625
PRESSURE DROP (IN OF H2O)		0.293
CONCENTRATION OF LIQUID OUT	(MG/L)	0.976
CONCENTRATION OF GAS OUT	(MG/L)	15.350

CAPITAL COSTS

COST OF FAN ($)	10600.65
COST OF PUMP ($)	13841.96
PACKING COST ($)	69145.67
STRUCTURE COST ($)	328426.38
TOTAL CAPITAL COST ($)	422014.67
DEBT SERVICE IN CENTS/1000 GALS	0.976

ANNUAL OPERATING AND MAINTENANCE COSTS

COST OF FAN POWER PER YEAR ($)	15411.38
PUMPING POWER COST PER YEAR ($)	2021.47
CHEMICAL,LABOR,MAINTENANCE COST PER YEAR ($)	19524.80
TOTAL OPERATING COST PER YEAR ($)	36957.67
OPERATING COST IN CENTS/1000 GALS	1.056

TOTAL COST IN CENTS/1000 GALS 2.032

STREAM MATRIX INPUT DATA

FLOW,MGD	NH3 IN	NH3 OUT	TEMPERATURE OF ENTERING WATER	LIQUID LOADING RATE	AIR LOADING RATE
10.000	40.000	1.000	70.000	654.90	2838.29

DECISION MATRIX INPUT DATA

COST OF ELECTRICITY $/KWH	AMORTIZATION FACTORS AMF1	AMF2	ALPHA IN PRESSURE DROP EQ.	BETA IN PRESSURE DROP EQ.	PER CENT TIME TOWER OPERATED	WET BULB TEMP	PUMP EFFICIENCY FACTOR	FAN EFFICIENCY FACTOR	COOLING TOWER EXIT TEMP
0.008	0.080	0.096	0.17E-07	0.00E 00	0.960	65.000	0.500	0.500	0.000

VERTICAL THICKNESS BARS,IN.	HORIZONTAL THICKNESS BARS,IN.	TYPE	VERTICAL SPACING OF BARS,IN.	HORIZONTAL SPACING OF BARS,IN.	COST OF SOLID FILL $/CU.FT.	CONSTRUCTION COST INDEX PHS	TOWER WIDTH FT.	INCREMENT HEIGHT FT.
4.000	0.250	1	4.000	1.750	6.000	1.000	72.790	0.250

CROSSFLOW TOWER

DIMENSIONS OF PACKING

HEIGHT (FT)	12.000
WIDTH (FT)	14.000
LENGTH (FT)	32.000
VOLUME (CU FT)	10752.0

OTHER DATA

EXIT LIQUID TEMPERATURE	37.458
LBS AIR /LBS WATER	3.337
PRESSURE DROP (IN OF H2O)	1.108
CONCENTRATION OF LIQUID OUT (MG/L)	5.978
CONCENTRATION OF GAS OUT (MG/L)	1.499

CAPITAL COSTS

COST OF FAN ($)	19309.04
COST OF PUMP ($)	4777.36
PACKING COST ($)	16077.67
STRUCTURE COST ($)	51928.39
TOTAL CAPITAL COST ($)	92092.47
DEBT SERVICE IN CENTS/1000 GALS	1.385

ANNUAL OPERATING AND MAINTENANCE COSTS

COST OF FAN POWER PER YEAR ($)	5369.75
PUMPING POWER COST PER YEAR ($)	243.74
CHEMICAL,LABOR,MAINTENANCE COST PER YEAR ($)	6287.11
TOTAL OPERATING COST PER YEAR ($)	11900.61
OPERATING COST IN CENTS/1000 GALS	2.126

TOTAL COST IN CENTS/1000 GALS 3.511

STREAM MATRIX INPUT DATA

FLOW,MGD	NH3 IN	NH3 OUT	TEMPERATURE OF ENTERING WATER	LIQUID LOADING RATE	AIR LOADING RATE
1.600	16.399	3.600	51.800	619.64	2412.83

DECISION MATRIX INPUT DATA

COST OF ELECTRICITY $/KWH	AMORTIZATION FACTORS AMF1	AMF2	ALPHA IN PRESSURE DROP EQ.	BETA IN PRESSURE DROP EQ.	PER CENT TIME TOWER OPERATED	WET BULB TEMP	PUMP EFFICIENCY FACTOR	FAN EFFICIENCY FACTOR	COOLING TOWER EXIT TEMP
0.008	0.080	0.096	0.26E-08	0.70E-09	0.960	32.000	0.750	0.750	38.000

VERTICAL THICKNESS BARS,IN.	HORIZONTAL THICKNESS BARS,IN.	TYPE	VERTICAL SPACING OF BARS,IN.	HORIZONTAL SPACING OF BARS,IN.	COST OF SOLID FILL $/CU.FT.	CONSTRUCTION COST INDEX PHS	TOWER WIDTH FT.	INCREMENT HEIGHT FT.
0.375	1.375	C	1.500	2.000	6.000	1.000	14.000	1.000

COUNTERFLOW TOWER

DIMENSIONS OF PACKING

HEIGHT (FT)	4.000
WIDTH (FT)	72.790
LENGTH (FT)	72.790
VOLUME (CU FT)	21194.0

OTHER DATA

EXIT LIQUID TEMPERATURE	66.915
LBS AIR /LBS WATER	0.238
PRESSURE DROP (IN OF H2O)	0.111
CONCENTRATION OF LIQUID OUT (MG/L)	11.854
CONCENTRATION OF GAS OUT (MG/L)	15.350

CAPITAL COSTS

COST OF FAN ($)	2160.17
COST OF PUMP ($)	8145.26
PACKING COST ($)	26341.20
STRUCTURE COST ($)	286505.30
TOTAL CAPITAL COST ($)	323151.94
DEBT SERVICE IN CENTS/1000 GALS	0.743

ANNUAL OPERATING AND MAINTENANCE COSTS

COST OF FAN POWER PER YEAR ($)	5869.04
PUMPING POWER COST PER YEAR ($)	878.90
CHEMICAL,LABOR,MAINTENANCE COST PER YEAR ($)	7557.70
TOTAL OPERATING COST PER YEAR ($)	14305.65
OPERATING COST IN CENTS/1000 GALS	0.408

TOTAL COST IN CENTS/1000 GALS 1.152

STREAM MATRIX INPUT DATA

FLOW,MGD	NH3 IN	NH3 OUT	TEMPERATURE OF ENTERING WATER	LIQUID LOADING RATE	AIR LOADING RATE
10.000	40.000	1.000	70.000	654.90	2838.29

DECISION MATRIX INPUT DATA

COST OF ELECTRICITY $/KWH	AMORTIZATION FACTORS AMF1	AMF2	ALPHA IN PRESSURE DROP EQ.	BETA IN PRESSURE DROP EQ.	PER CENT TIME TOWER OPERATED	WET BULB TEMP	PUMP EFFICIENCY FACTOR	FAN EFFICIENCY FACTOR	COOLING TOWER EXIT TEMP
0.008	0.080	0.096	0.17E-07	0.00E 00	0.960	65.000	0.500	0.500	67.000

VERTICAL THICKNESS BARS,IN.	HORIZONTAL THICKNESS BARS,IN.	TYPE	VERTICAL SPACING OF BARS,IN.	HORIZONTAL SPACING OF BARS,IN.	COST OF SOLID FILL $/CU.FT.	CONSTRUCTION COST INDEX PHS	TOWER WIDTH FT.	INCREMENT HEIGHT FT.
4.000	0.250	1	4.000	1.750	6.000	1.000	72.790	0.250

DEFINITIONS OF FORTRAN SYMBOLS

Computer Symbol	Definitions and Comments
ACEG	Debt service cost of tower, cents/1000 gallons
ACPG	Total cost of tower, cents/1000 gallons
ALPHA	α in the pressure drop equation
AMF1	Amortization factor for equipment
AMF2	Amortization factor for structures
AVGCL	Concentration of liquid coming out of the tower, mg/l
AVGCG	Concentration of gas coming out of the tower, mg/l
BETA	β in the pressure drop equation
CAP	Total capital cost of tower, dollars
CCI	FWPCA Construction Cost Index
CKWH	Cost of electricity, cents/kilowatt hour
CLINP	Concentration of liquid entering the tower, mg/l
CLOUT	Desired concentration of liquid coming out of tower, mg/l
CPA	Cost of packing, dollars/cubic foot
DELP	Pressure drop, inches of water
DELZ	Height of numerical integration interval. For the crossflow tower, DELZ = 1 foot produces adequate results. For the counterflow tower, DELZ = .25 feet produces adequate results
EF	Efficiency of the fan
EP	Efficiency of the pump

DEFINITIONS OF FORTRAN SYMBOLS

Computer Symbol	Definitions and Comments
FAN	Cost of fan, dollars
FANPW	Cost of fan power per year, dollars
GP	Gas loading rate, $lb/ft^2/hour$
HS	Horizontal spacing of splash bars, inches
HT	Height of packing calculated by the program, feet
HTH	Horizontal thickness of splash bars, inches
LAM	Chemical, labor and maintenance cost per year, dollars
LENTH	Length of packing calculated by the program, feet
LP	Liquid loading rate, $lb/ft^2/hour$
NCASE	Program control: the number of cases to be executed by the program
OCEG	Operating cost of tower, cents/1000 gallons
OPER	Total operating cost per year, dollars
PCTIM	Percent time of operation, %
PACK	Packing cost, dollars
PUMP	Cost of pump, dollars
PUMPW	Pumping power cost per year, dollars
Q	Volume flow, mgd
RATIO	Ratio of lbs of air/lbs of water
STRUT	Structure cost, dollars

DEFINITIONS OF FORTRAN SYMBOLS

Computer Symbol	Definitions and Comments
TE	Desired exit temperature of liquid for cooling tower calculations, ^{o}F. If TE is set equal to 0, the program assumes a stripping tower calculation. If TE is non-zero, the program assumes a cooling tower calculation
TH2O	Temperature of entering liquid, ^{o}F
TLIQ	Exit temperature of liquid, ^{o}F
TWB	Wet bulb temperature of gas, ^{o}F
TYPE	Program control: type of tower; if set equal to 0, the input is for a crossflow tower; if set equal to 1, the input is for a counterflow tower
VS	Vertical spacing between splash bars, inches
VTH	Vertical thickness of splash bars, inches
VOL	Volume of packing computed by program, cubic feet
W	Width of crossflow tower: this is input to the crossflow calculation in multiples of DELZ. For the counterflow calculation, this is a calculated output and need not be supplied as input. Units are in feet.

DEFINITIONS OF ALGEBRAIC SYMBOLS

Symbol	Definitions and Comments
A	L'/G'
A_f	Annual cost of fan power, dollars/year
A_l	Annual cost of labor, chemicals and supplies, dollars/year
A_p	Specific surface area, sq ft/cu ft
A_w	Annual cost of pumping, dollars/year
B	dw/H_a
C_f	Cost of loose wood fill, dollars
C_k	Cost of electricity, cents/KWH
C_p	Specific heat of water, BTU/lb/^oF = 1.0
C_s	Cost of steel structure, dollars
C_w	Cost of solid wood fill, dollars
D	Diffusivity in the liquid phase, sq ft/hr
dw	Increment of tower width, ft
dz	Increment of tower height, ft
E_f	Efficiency of fan, factor
E_p	Efficiency of pump, factor
f	Fanning friction factor
g	Acceleration due to gravity, 4.17×10^8 ft/hr^2
G	Air flow rate, lb/hr/sq ft
G'	Air flow rate, lb moles/hr/sq ft
G_E	Equivalent air mass velocity for pressure drop relations, lb/hr/sq ft

DEFINITIONS OF ALGEBRAIC SYMBOLS

Symbol	Definitions and Comments
h	Enthalpy of gas, BTU/lb
h^*	Enthalpy of air saturated with water vapor at the temperature of the water at the center of the element, BTU/lb of dry air
H_a	Overall height of a transfer unit for ammonia, ft
H_g	Height of gas phase transfer unit, ft
H_l	Height of liquid phase transfer unit, ft
H_t	Height of a transfer unit for cooling, ft
H_T	Horizontal thickness, in.
H_S	Horizontal spacing, in.
i	Increment subscript increasing in direction of air flow
j	Increment subscript increasing down the tower
K_a	Enthalpy transfer coefficient lbs/(hr)(sq ft)
K_g	Gas mass transfer coefficient, lb moles/(hr)(sq ft)(atm)
l	Length of tower (perpendicular to air flow in crossflow tower), ft
L	Liquid loading rate, lb/hr/sq ft
L'	Liquid loading rate, lb moles/hr/sq ft
m	Henry's law constant, dimensionless
P_c	Percent of time tower is operating per year
ΔP	Overall pressure drop, in. of H_2O
ΔP_1	Pressure drop due to obstruction of the packing, in. of H_2O
ΔP_2	Pressure drop due to free falling drops of water, in. of H_2O

DEFINITIONS OF ALGEBRAIC SYMBOLS

Symbol	Definitions and Comments
Q	Liquid flow rate, mgd
R	mG'/L'
S_F	Vertical free fall of a water drop, ft
T	Water temperature, ^oF
T_g	Outlet wet bulb temperature of gas, ^oF
V_o	Constant for Johnstone and Singh relationship
V_T	Vertical thickness, in.
V_S	Vertical spacing, in.
w	Width of tower (parallel to air flow for cross sectional tower), ft
x_i	Concentration of ammonia in water, mole fraction
y_i	Concentration of ammonia gas in air, mole fraction
y^*	Concentration of ammonia in gas in equilibrium with the liquid at the midpoint of the incremental volume according to Henry's law, mole fraction
z	Tower height, ft
α	Pressure drop relation constant
β	Pressure drop relation constant
ρ	Density of water, lb/cu ft
ρ_g	Density of dry air, lb/cu ft
μ	Vicosity of water, lb/ft hr

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